4TH QUARTER 1958

ALLIS-CHALMERS Electrical REVIEW

ALLIS-CHALMERS Electrical REVIEW

THE COVER

FORGED GENERATOR SHAFT will be installed in a 22,300-amp, 860-volt, 350-rpm, 4060-kw generator for the Model C Stellarator. Four such generators, a 7000-hp wound-rotor motor, and an 80-ton flywheel make up each of the three motor-generator sets used for power supply.

The Model C Stellarator is an experimental machine designed to reach and confine temperatures of many millions of degrees — a major effort toward the realization of controlled thermonuclear fusion. *Allis-Chalmers Staff Photo by Michael Durante*

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AIR SWITCH *Serves* LOAD TAP-CHANGING TRANSFORMER

90,000-KVA regulating transformer with air-break load tap changer is prepared for shipment. Unit provides controlled voltage for battery of rectifier transformers. (FIGURE 1)

by **S. L. FOSTER**
Transformer Department
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Load tap-changing transformers used in industrial applications can impose heavy demands on circuit interrupters. Air switches can be used to advantage up to 125,000 kva.

AIR-BREAK SWITCHING is being used in place of the conventional oil-break switching on a recently developed transformer load tap changer. The equipment can be used on medium-sized transformers, is easy to maintain and has a long service life. The unit shown in Figure 1 will serve an aluminum reduction plant where service conditions are severe. Over 100,000 operations per year in this service are common.

Interrupting problem solved

The air-switched load tap changer uses essentially the same scheme as is used for load tap changing on large power transformers. The circuit arrangement is shown in Figure 2. A center-tapped reactor bridges the tapped sections of the transformer winding, and a dial selector switch makes the desired tap connections. The sequence of operations in making a tap change from tap 1 to tap 2 is given in the table in Figure 2. The tap selector switch is not required to interrupt the circuit, since the load-break switches are in series with the reactor and the tap selector contacts.

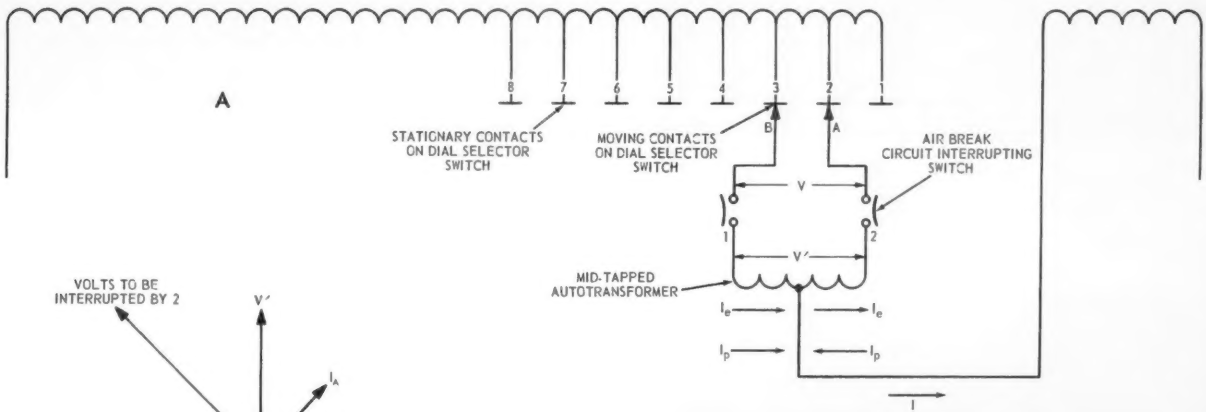
Common to all reactance-switched load tap changers, the current through the circuit interrupting switch lags the voltage by almost 90 degrees. This phase lag causes a difficult interrupting problem, since the voltage tending to maintain the arc is maximum at the time the arc current is zero. The vector relations of Figure 2*b* exist in the circuit of Figure 2*a* when the load of the transformer has unity power factor. It might be expected that the interrupting problems would be changed by the power factor of the load. However, the vector diagram of Figure 2*c* shows that at 80 percent power factor the current through a switch still lags the voltage across that switch by about 90 degrees. This is because the voltage which appears across the reactor (V') after the switch is open is always 90 degrees ahead of the load current (I_p), whereas the existing current of the reactor I_e remains 90 degrees behind the voltage across the transformer tap (V).

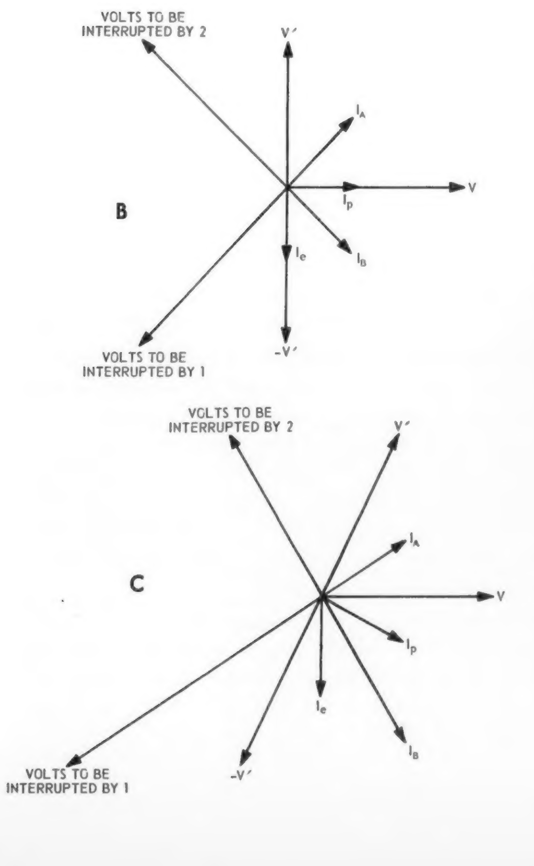
The change in phase relationship, however, increases the interrupting requirements of switch 1 in series with contact *B*. Since the power factor of most transformer loads is approximately 90 percent, it is common to rate the life of load tap changers on the basis of interruption with 90 percent power factor.

For the normal load condition the oscillograms shown in Figure 3 were recorded. The operation starts with the switch closed and current flowing. The switch operating mechanism starts to move at point *a*, and the contacts part at point *b*, with arcing taking place across the open contacts as noted in the voltage oscillogram. The circuit is finally interrupted at point *c* with a zero of current.

In an oil switch it is necessary to extinguish the arc well before the moving contacts complete their travel. For low maintenance and reasonable oil deterioration the arcing time is usually limited to about one cycle. Arcing time is not critical in an air switch, since the arc leaves the point of contact of the switch and is driven into arc chutes where it is cooled and extinguished. Since the forces driving the arc into the chutes are electrical and thermal, not mechanical, it is not necessary to extinguish the arc before the mechanical operation is complete. It is necessary, however, to have sufficient mechanical opening of the contacts to prevent restrike or arc-over after the circuit has been interrupted. The products of arcing in air are gaseous and are carried away by the air. It is desirable to keep the air switch compartment dry, because some of the gases formed by an arc in air can become acid when mixed with water vapor. If the compartment is kept above ambient temperature and well ventilated, the gases from arcing will be dissipated to the atmosphere, leaving no residue for contamination.

A power transformer can carry overloads for a short time because of its large thermal capacity. These overloads may range up to twice normal load. Since the load

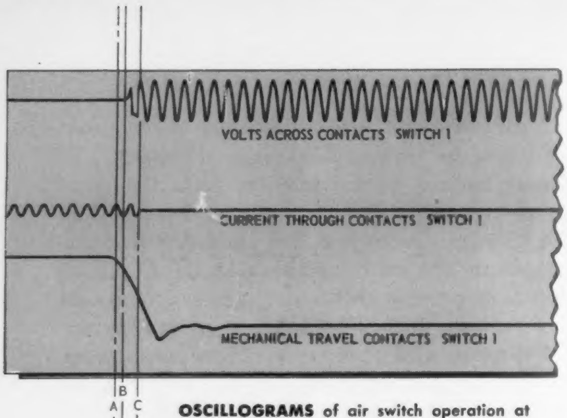




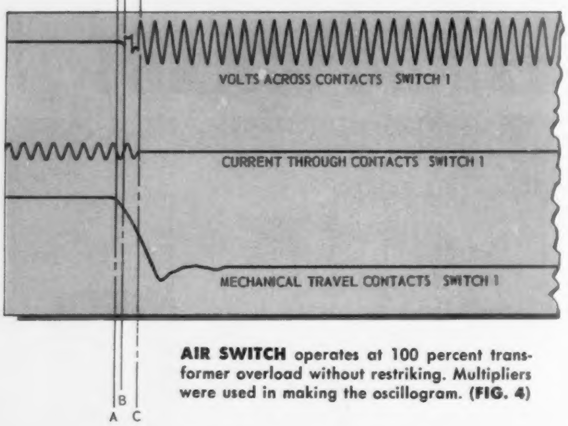
SEQUENCE OF OPERATION

Position Number	A To	B To	Switch 1	Switch 2
1	1	1	Closed	Closed
Transition	1	1	Open	Closed
	1	2	Open	Closed
2	1	2	Closed	Closed
Transition	1	2	Closed	Open
	2	2	Closed	Open
3	2	2	Closed	Closed

LOAD TAP-CHANGER operating sequence is detailed in table below the circuit *A*. Vectors in *B* are the relations of current and voltage of the load tap-changer circuit with transformer carrying unity power factor. Vectors in C are circuit operating conditions when the transformer is carrying a lagging power factor load. **(FIGURE 2)**



OSCILLOGRAMS of air switch operation at full load indicate that voltage exists between open contacts with minimum arcing. **(FIG. 3)**



AIR SWITCH operates at 100 percent transformer overload without restriking. Multipliers were used in making the oscillogram. **(FIG. 4)**

PRINCIPAL PARTS of the load tap changer are the operating mechanism at lower left, tap selector switch at the top, and air switch at lower right. **(FIGURE 5)**

tap changer will usually be required to operate during these periods of overload, one of the characteristics which must be met for successful operation is that the load tap changer operate with the transformer at 100 percent overload. Figure 4 illustrates that it is not difficult to meet this requirement with the air switch. Referring to Figure 2*c*, one can see that the current and voltage will not be quite double when the load is increased 100 percent. The blowout force of the arc interruption is increased, since the higher current arc is driven more violently into the arc chutes, resulting in very little increase in arcing time. The cycle of interruption is the same as Figure 3, except that the scale has been changed to keep the magnitude of the oscillogram traces about the same. It will be noted that the arcing time has increased about ½ cycle for two times the load on the transformer. Because relatively large clearances are required in the air switch compartment, air switch application is limited to power transformers of the lower voltage ranges.

Interlock insures correct sequence

The mechanical parts of the load tap changer are shown in Figure 5. The mainstay of this assembly is a vertical drive shaft in the control compartment which extends into the tap selector compartment. Heavy gears connect the vertical shaft to the drive shafts of the tap selector and interrupting contactor. This insures that there is a positive interlock between the operation of the tap selector dial switch and the circuit interrupter. The air switch includes three-phase vertical lift contactors. Each contactor is operated by a linkage driven from the interrupter drive shaft. When the main drive shaft in the control compartment rotates to make a tap change, the linkage holding the circuit interrupting switch closed is operated at the proper time to open the circuit. The switch is either forced open by the linkage or will drop open by gravity when the linkage is tripped. This provides a positive fail-safe operating mechanism. Full-load operating tests on these contactors have shown that the contacts have a life, determined by erosion of contact material, greater than 400,000 operations of the load tap changer under full transformer load.

When the circuit has been interrupted, the tap selector dial switch can move to select the tap without causing an arc in its compartment. Since there is no arcing, the compartment is oil filled to reduce its size. The oil can be maintained under a blanket of inert gas which will keep the oil in good condition. Dial-type selector switches of this kind have a mechanical life of several million operations; therefore, only occasional mechanical inspection of the tap selector dial is required.

In the medium-sized power transformer of the lower voltage class, the load tap changer operates successfully with an air switch. The combination of a standard oil-insulated tap selector switch and air switch on a severe duty cycle will provide long life and low maintenance.

COORDINATING NETWORK RELAYING

by **A. H. KNABLE**
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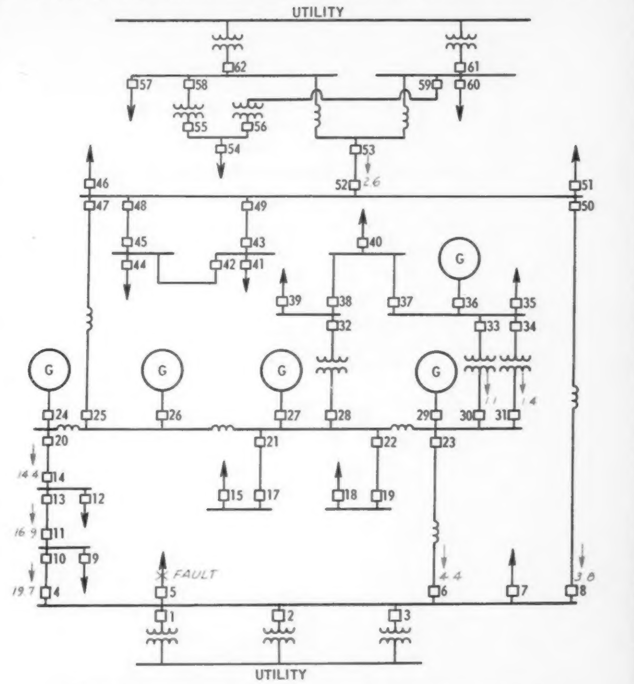
By adding a few simple steps to the common methods of relay coordination for radial systems, more complex industrial networks can be analyzed.



ACTUAL INDUSTRIAL SYSTEM is used as example of how to coordinate breaker tripping in a network. Only currents above relay pickup values are shown for one possible fault condition. **(FIG. 1)**

IN A NETWORK-TYPE SYSTEM, as in a radial system, the circuit breaker nearest the fault opens first and the circuit breakers farthest from the fault (nearest the source) open last. However, in a network there are multiple paths between fault and sources, resulting in a shift of a circuit breaker's relative operating time position with respect to adjacent breakers when various fault positions on the system are considered. In other words, one cannot determine by direct observation which breaker should operate before another to satisfy all possible conditions. Furthermore, unlike a radial system, there are many different current magnitudes through any one breaker.

When coordinating network-type systems, the following points should be kept in mind:

1. That the multiple time sequence of breaker operations must be reduced to one resultant time sequence satisfactory to the overall system.

2. That the one critical current must be determined from the multiple currents in each breaker.

Establishing a current distribution in the system for each fault condition serves to determine the various paths that must be followed from fault to source, and to point out what paths have currents below relay pickup. The areas below pickup require no further consideration for that particular case. This procedure is essentially the same as for a radial system except for the tracing of the multiple paths instead of a single path.

The time-sequence tabulation evolves from a fault current contribution diagram showing the various fault current paths for each fault location. The fault current contributions can be indicated on a diagram, as shown in Figure 1. These currents come from a long-hand or network calculator short-circuit study. By following the fault contribution diagram from fault to source and recording the breakers in sequence, an initial relative time-sequence tabulation can be constructed, as shown in Figure 2. A non-repeat retabulation, Figure 3, serves as an intermediate step to the final compact relative time-sequence tabulation in Figure 4.

A time-current relationship in tabular form, suitable for visual inspection, must be known to establish the critical

current for each breaker. This table is needed to compare the current in conjunction with breaker time sequences.

There are three possible current combinations to be observed:

1. From large to small magnitude.
2. From small to large magnitude.
3. Equal magnitudes.

With the established sequence the small to large current combination is the most severe condition to consider. This combination determines the critical current.

The critical breaker currents evolve from a tabulation of the joint time-current relation, shown in Figure 5. The currents in amperes are then converted to current multiples by using the following equation:

$$I_{\mathrm{mult}} = \frac{I_{\mathrm{amp}}}{\text{CT ratio x tap setting}}$$

The tap setting refers to pickup point of relay. Assume in this particular example that the currents in kiloamps and multiples are the same. By remembering that the most severe current condition is from small to large in the breaker adjacent to the one being considered, the critical current can be established as shown by the currents underlined. The largest current is the critical current for the breakers in column t_1. Since each breaker is to be considered in turn, it is not necessary to consider more than the immediately adjacent breaker. All other conditions to be satisfied will be either amply or more than amply met. The normal relation (when arrow links two critical currents) permits the use of the simple equation:

$$t_n = (t_{(n-1)} \text{ x margin factor})$$

The margin factor is an arbitrary time that is set up between breakers.

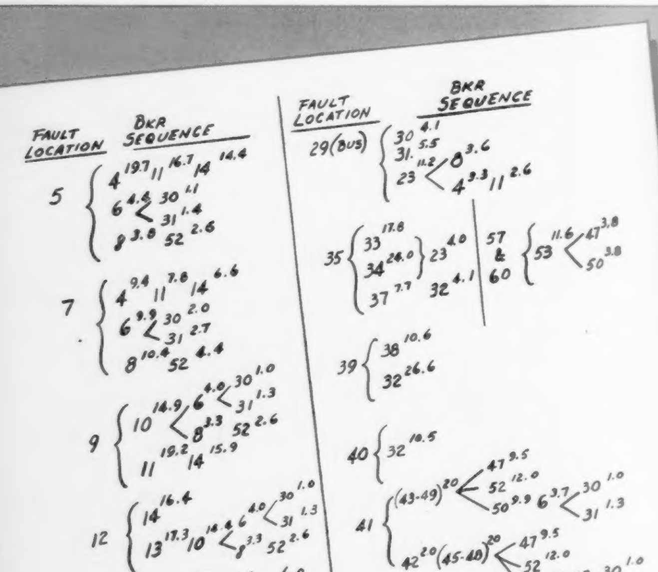
Where the arrow does not link critical currents, then one of the following equations is used:

When I used is less than I critical, as in the case of establishing the critical current for breaker 14,

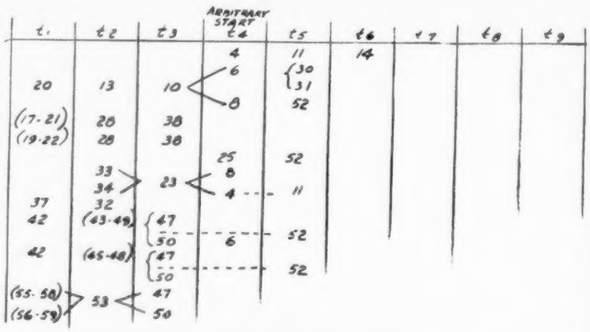
$$t_n = (t_{(n-1)} + \triangle t) \text{ x margin factor}$$

When I used is greater than I critical, as in the case of breaker 4,

$$t_n = (t_{(n-1)} - \triangle t) \text{ x margin factor}$$



RELATIVE TIME-SEQUENCE TABULATION is established by following the diagram from fault possibility to source. Fault currents in kiloamperes are added for future reference. **(FIGURE 2)**



TIME SEQUENCE OF BREAKERS t_1, t_2, etc., is established from Figure 2. Since tabulation might go either direction, t_4 was taken as starting point. **(FIGURE 3)**

t_1	t_2	t_3	t_4	t_5
20	13	10	8	52
(17-21)	28	38	6	14
(19-22)	23	4	11	30
25	32	47		31
33	(43-49)	50		
34	(45-48)			
37	53			
42				
(55-58)				
(56-59)				

FEEDER — SOURCE

DATA of Figure 3 is compressed. Breakers having no time to their left are moved to t_1 column. Breakers that follow are also moved to left if remaining sequence permits. **(FIGURE 4)**

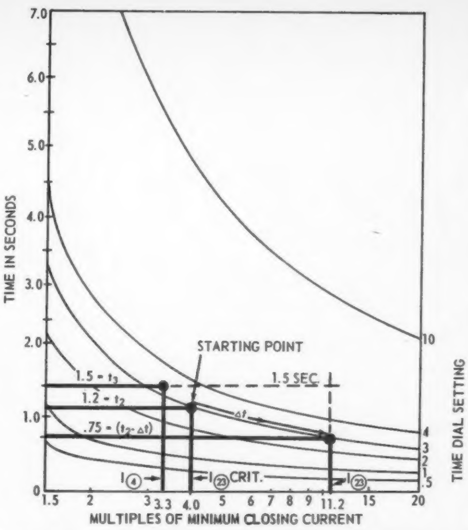
Δt is taken from the relay curve, as shown in Figure 6. The figure shows how to determine t_3 for breaker 4, using t_2 for breaker 23 as a starting point.

There are two ways that the data can be presented for application:

One is to present the relative time sequence of the breakers and the joint time-current diagram. This form requires a minimum of system data. Data such as CT ratios, type of overcurrent relays used, and pickup currents (tap settings) need not be known.

A second way is to present the tap settings and time lever settings. This form requires that CT ratios, tap settings based on pickup, and type of over-current relays are known.

The first method is in exceptionally useful form, since the major part of the coordination problem is completed without a detailed knowledge of system components.



OVERCURRENT RELAY TRIPPING CURVES illustrate method of using Δt to keep relay time settings as low as possible. When utility relay settings necessitate close coordination, Δt becomes significant. **(FIG. 6)**

TIME-CURRENT RELATIONS are compiled on single table from which breaker relay settings may be determined. Currents are taken from Figure 2, while sequence is checked with Figure 4. **(FIGURE 5)**

CURRENT-TIME RELATION

t_1	t_2	t_3	t_4	t_5
20	13	10	8	52
18.8 →	16.4 →	13.2 →	2.9 →	2.6
			3.8	2.6
			10.4	4.4
		14.9	3.3	2.6
	17.8	14.4	3.3	2.6
			6	30
				31
			4.4	1.2
			9.9	2.4
		14.9	4.0	1.2
	17.8	14.4	4.0	1.2
18.8	16.4	13.2 →	3.7 →	1.2
5.2	4.1	2.9		
42	45-48	50		
20 →	20 →	9.9	3.7	1.2
	20	9.9	3.7	1.2
		10.1	3.7	1.2
	43-49			
20 →	20	9.9	3.7	1.2
	20	9.9	3.7	1.2
		47		52
	20 →	9.5		
				12.0
	20			
20	20	9.5		
20	20			12.0
	45-48			
20	20	9.5		
20	20			12.0
	20	9.5		
	20			12.0

t_1	t_2	t_3	t_4	t_5
17-21	28	4	11	14
		19.7 →	16.9	14.4
		9.4	7.8 →	6.6
			19.2	15.9
		38		33
22.7 →	1.4 →	6.0		31
22.7				0.9
19.22				
22.7	1.4	6.0		
22.7				
25				0.9
				52
2.5				2.6
	1.0	4.0		
10.4				4.6
33	23	4		
	11.2 →	3.3	2.6	
17.8 →	4.0			
34				
24.0	4.0			
			8	
	11.2		3.6	
55-58	53	47		
14 →	3.0			
56-59				
14	3.0			
	11.6	3.8		
		50		
	11.6	3.8		
37	32			
7.7 →	4.1			

LOCK OUT ACCIDENTS with SAFETY INTERLOCKS

by **R. F. SCHOOF**
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Allis-Chalmers Mfg. Co.

THREE-WAY INTERLOCK on disconnect switch handle of new medium voltage motor starter prevents opening of disconnect when contactor is closed, prevents closing of contactor when the disconnects are open and permits admittance to the contactor compartment only when the disconnect handle is in the "Off" position.

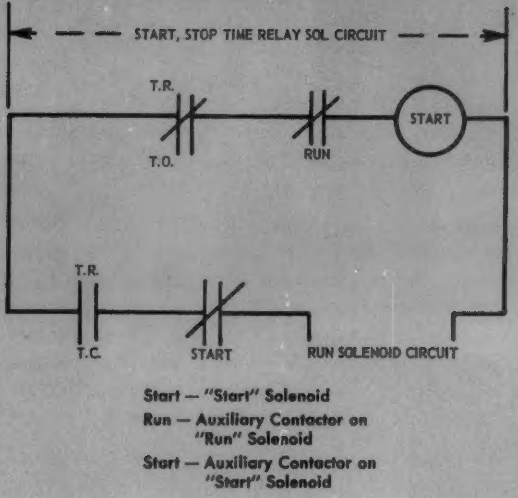
Safety interlocks can be arranged for any machine and any operating condition. Here is a basic discussion on their application.

ONE OF THE BRIEFEST DEFINITIONS of the term "interlock" is that given in the National Electrical Manufacturers Association's standards: "An interlock is a device actuated by the operation of some other device with which it is directly associated to govern succeeding operations of the same or allied devices."

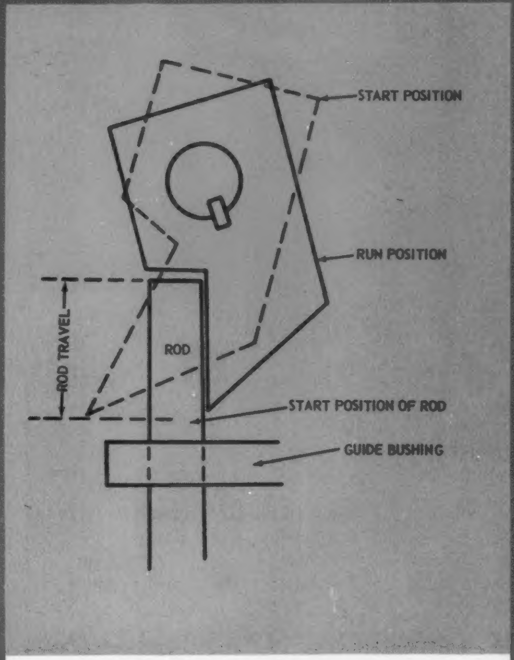
Adequate machinery guarding is, of course, basic to any organized safety program. Human habits and practices in the interest of safety are difficult to establish and maintain, but mechanical gains are permanent. It is generally accepted by most safety authorities that approximately one-fourth of all permanent partial disabilities result from machine-caused injuries. Safety educational programs for the personnel, however, are not good enough. Interlocking of equipment, either by the manufacturer or by the user, is considered a necessary part of safe design and installation.

Failure to give a proven need proper attention has caused more injuries and unnecessary expense than any other consideration. As a general rule the starting point in determining the need for interlocking is to examine the accident history of the machine or equipment. If there is any history of injury or major material damage, the question of whether the use of an interlocking device would have prevented the injury should be carefully considered. It should be remembered that interlocking devices and their application go beyond protecting the point of operation during the normal work process.

If adjustments are required in dangerous areas of the machines, interlocks can be provided which will require stopping the machine to make the adjustment. This may be in the form of an interlocking guard, the interlocking of adjustment tools with the starter, etc.



SIMPLE RELAY CONTACT CIRCUITS can be used to prevent improper sequences in applying electrical equipment. Reduced-voltage starter includes time-delay relay to assure proper sequence of the "start" and "run" contactors despite human errors. **(FIGURE 1)**



MECHANICAL INTERLOCK LATCHES vary in form. The rod and latch type shown prevents accidental closing of the reduced-voltage starter "run" contactor while the "start" contactor is energized. **(FIGURE 2)**

In a series of process operations interlocks can be provided which will afford the necessary safety for operator and equipment in the event of failure of sequence timers or controls.

Selecting interlocks

Machine control systems in many cases combine various electrical, mechanical, hydraulic, and pneumatic interlocked elements. Of the four types, electrical systems are predominant.

Electrical systems

Electrical interlocking has three advantages: lower cost, greater flexibility and ease of servicing. However, there are problems which can arise in electrical interlocks and precautions should be taken against them. These problems may result from the following:

1. Breaking of circuits.
2. Short circuits.
3. Grounds.
4. Residual magnetism in relays and solenoids.
5. Direct failure of the limit switch or other actuator.

The most common electrical interlocks are used to prevent trouble despite an error by the operator. For this reason, enclosures for controllers, switchgear and other apparatus often have interlocks to de-energize high voltage compartments when access doors are opened.

Assuring a proper control sequence is another important use of electrical interlocks. Reduced-voltage open-transition motor starters use both electrical and mechanical interlocks for this purpose. The electrical control circuit includes the elements shown in Figure 1. The normally closed "run" contact shown is an auxiliary on the "run" contactor, preventing operation of the "start" solenoid when the controller has progressed to "run" position. Similarly, the normally closed "start" contact in the "run" circuit prevents energizing the "run" circuit when controller is in the "start" portion of the cycle.

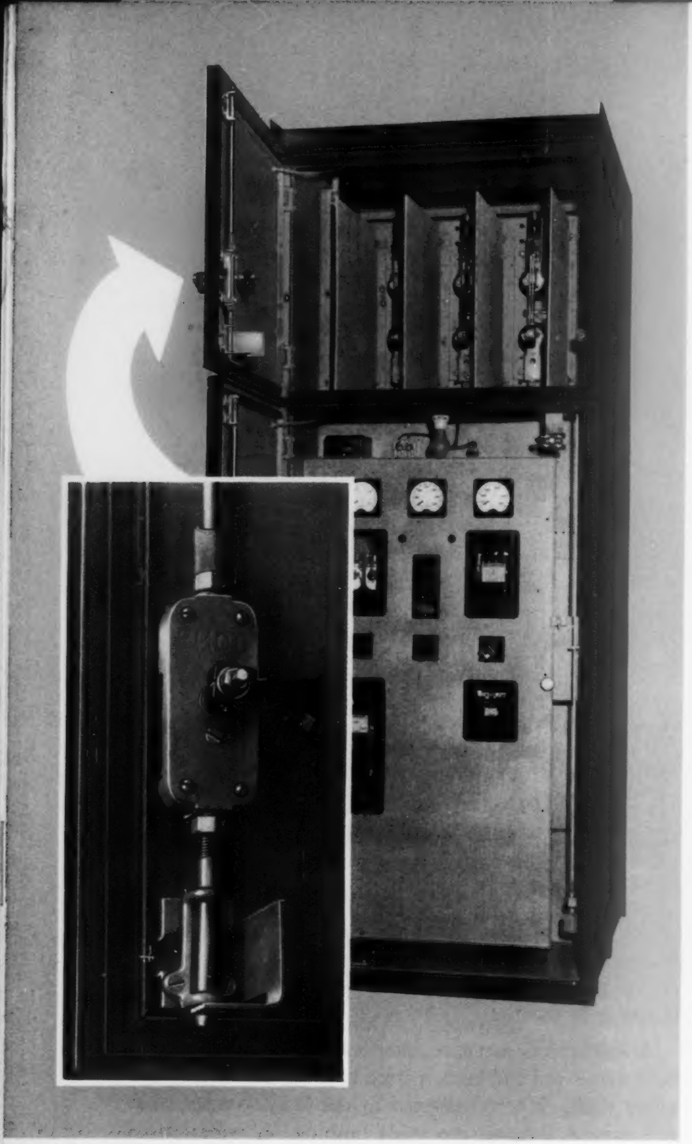
A mechanical sequence interlock for this purpose can be a simple rod and latch, a latch keyed to the "start" contactor shaft, or a rod pivoted to the "run" contact shaft and passing through the guide bushing. A typical latch configuration is shown in Figure 2.

A newly designed motor starter, shown in Figures 3 and 4, includes a new type door interlock. Normally units with rear access do not have load-break disconnect switches. Where a positive-acting disconnect interlock is needed, two interlocks, one on the disconnect handle and the other actuated by the door, prevent opening the disconnect under load or operating the contactor with upper door open.

A new type of high voltage air-break contactor utilizes both electrical and mechanical interlocks to protect the operator. The door latch is connected to a vertical control rod which is prevented from moving by an interference-type mechanical interlock. In addition, a solenoid plunger interlock is used to latch the push rod in position when the load side of the contactor is energized.

Mechanical systems

Interlocking secured by purely mechanical devices is quite common, but extensive mechanical interlocking systems governing many functions of one machine or a group of machines are seldom found because of the complication of the necessary shafts, gears and linkages.



ELECTRICAL DOOR INTERLOCK de-energizes motor starter contactor when upper compartment door is opened, so that the hook-type disconnects cannot be opened under load. (FIGURE 3)

Mechanical interlocking systems used on electrical equipment are of two basic designs: interference, or latch type, and the teeter-totter type. The teeter-totter type has a good record of performance, but the weight and size of the devices required for strength are primary disadvantages.

Interference systems using jam bars, latches and other frictional devices are usually small and are more common in modern designs. Their one major difficulty is an inherent tendency to jam the entire mechanism because of friction, wear, or misalignment.

Hydraulic systems

The operational cycles of hydraulic machines follow one of three types of sequences — pressure, position, or time. The most positive is position sequence, in which one operation does not follow another until a ram has reached its predetermined point of travel. Electric limit switches are commonly used to control this sequence. Cam-operated valves are used occasionally with safety but are not too desirable when the next machine in sequence is at some distance.

Pressure control systems utilize pressure-sensitive switches to close the circuit for succeeding operations. Theoretically they are ideal for many applications; however, pressure transients can be a problem. Pressure-sensitive switches cannot be used unless the system has good pressure regulation. Workpiece jamming can also cause difficulty. Secondary interlocks are essential for safe operation of pressure-controlled systems.

Time controls using dashpots or various electrical timers are generally reliable and widely applied. On critical installations, however, it is necessary that mechanical interlocks be provided.

Electrical controls, because of their simplicity of installation, are widely used for controlling hydraulic machines. Circuits are available to stop ram movement or release all pressure upon hydraulic system failure or loss of mechanical motion. Controls may be designed so that jamming of workpieces will not cause machine damage.

Two-hand and four-hand operator controls are used as point of operation safeguards on many presses. These safety controls are wired in series with the control solenoid or other clutch actuator. Each control station, whether for two hands, four hands, one hand and one foot, or other arrangement, operates through individual relays. These relays have time-out features requiring that all contacts must be actuated at approximately the same moment or the cycle must be restarted. Tripping or blocking one of the controls is thereby prevented. Some manufacturers provide means for adjusting this time-out feature. Figure 5 shows a typical foot-and-hand control.

A rather broad subfield in hydraulic safety interlocks is the control of pumps and pressure generators used on large presses. Fundamental considerations are providing for emergency stop, standard undervoltage, overload and short-circuit protection. Indicator lights may be used to indicate each operation.

A matter of concern when operating large equipment is the protection of the machine itself. Hydraulic machines are susceptible to damage when operating with oil that is too cold or too hot. Circuits have been devised which make it impossible for the pumps to start until the oil temperature is within the proper range. The circuit includes automatically controlled interlocked immersion heaters. A third safety interlock prevents continued operation when the oil temperature rises above safe maximum.

Pneumatic systems

Pneumatic controls with safety interlocks are quite common throughout industry and are noted for their simplicity and reliability. Figure 6 shows a typical two-hand control system. Stop systems operating on a vacuum are particularly foolproof, as the breaking of a pipeline or other device gives a positive control action.

PAPER CUTTER REQUIRES two hands to operate. Removal of either hand instantly stops the cutter blade travel. **(FIGURE 4)**

SIMULTANEOUS use of two hands and two feet is required to operate hydraulic press to prevent injury to the operator. **(FIGURE 5)**

Pneumatic safety interlocks are used both for operator protection and machine protection. Machine protection is frequently the only consideration given but is important because machines can be quite large and complex and damage might be costly. Interlock protection can minimize breakdowns and loss of productive output for succeeding operations.

Air-operated devices and machines are, in general, fast and therefore many accident exposures are presented. Timing of pneumatic components is critical and must be considered during the design and installation. Safety interlocks are commonly provided to stop the machine when air pressure falls below the safe minimum. Sequence timing must be positive and is usually accomplished through electric limit switches or pneumatic cam-operated valves.

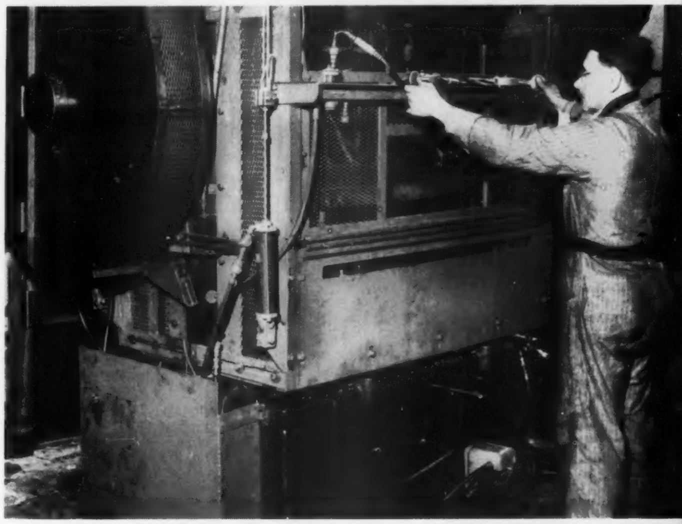
Press controls utilizing only air devices are now being used. This arrangement is possible through the recent development of non-tiedown and single-stroke air valves. The non-tiedown valve is designed to supply inlet air from two palm button valves almost simultaneously to initiate press operation. Any attempt to tie down one of the buttons results in air being exhausted at the non-tiedown valve. A sensitivity control may be adjusted to require either simultaneous operation or a small degree of time lag between operation of the two buttons.

The single-stroke valve makes repeating of the press cycle impossible even though both buttons are held down. Pressure must be removed from the inlet port before the valve can pass air for the succeeding cycle.

Adequate safety device cost is low

Through experience and as a result of accidents, many excellent safety devices and interlocks have become standardized. In many cases safety interlocks of a specific nature are now required by state codes.

When heavy machinery is installed, revamped or reapplied, a qualified safety engineer should be consulted to be sure those working with the machine are thoroughly pro-



AIR-OPERATED press uses two-hand pneumatic pushbuttons and interlocked gate guard to keep operator's hands out of danger. **(FIG. 6)**

tected. The machine, whether operated by electrical, mechanical, hydraulic or pneumatic means, can usually be adequately protected with the addition of a few inexpensive interlocking devices.

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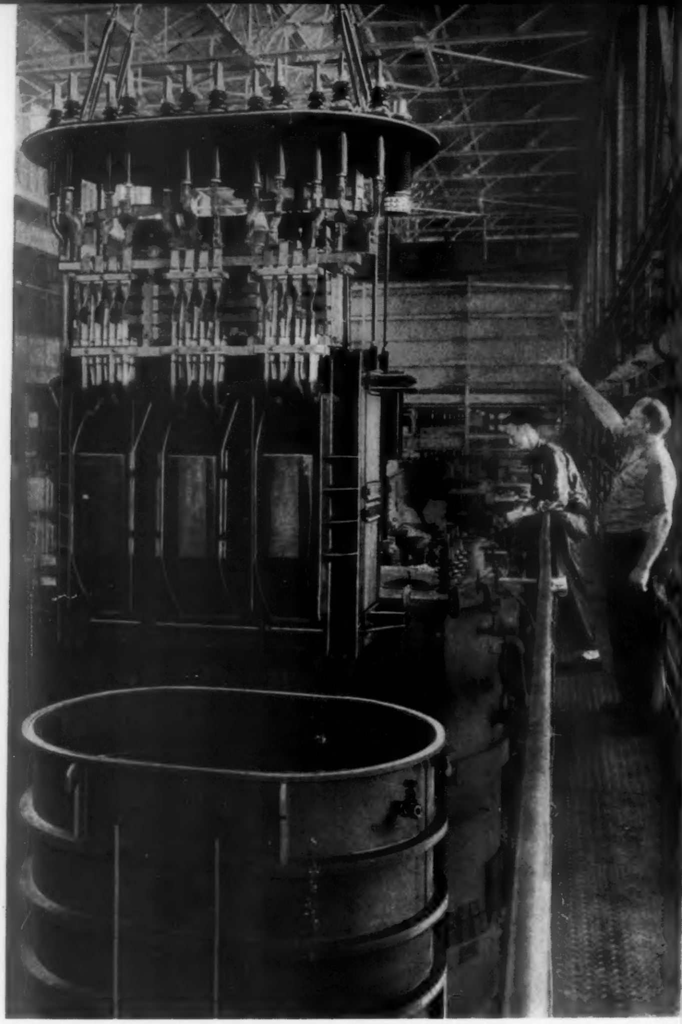
Designing Rectifier Transformers with Phase Shift



CORE AND COIL ASSEMBLY is lowered into the tank. All connections to bushings are completed before tanking. (FIGURE 1)

by JOHN A. EBERT
Transformer Department
Allis-Chalmers Mfg. Co.

Novel winding arrangement in rectifier transformer eliminates separate phase-shifting unit. Design improves regulation and efficiency, and simplifies station layout.

THE CURRENT INTEREST in finding new uses for aluminum in our rapidly expanding economy has stimulated demand for the metal, resulting in expanding production facilities. Light, weather-resistant aluminum will soon be produced by a large aluminum company in a new plant located near, and supplied by power from, the St. Lawrence seaway development. Approximately 380,000 kva will be required continuously by this plant.

Transformer has large secondary kva rating

To supply current to the mercury-arc rectifiers used in aluminum reduction, a specially designed transformer is required. The rectifier transformer carries current for the anodes for only part of a cycle in each of its multiple phases. This means the kva rating of the rectifier transformer secondary is higher than the kva rating of the primary, because the rms value of the secondary current is based on the rectified current. The kw output of the rectifier is therefore less than the equivalent kva rating of the transformer.

Low reactance in a rectifier transformer is desirable, since leakage reactance unfavorably affects the regulation of the dc voltage of the rectifier. However, the transformer must be self-protecting under short-circuit conditions, and this together with reactance must be considered in the design. A mechanical force five to six times the short-circuit force normally encountered in a power transformer of an equivalent size will be exerted on a rectifier transformer in the event of a "backfire" of the rectifier. Such backfires occur when the valve action of the rectifier

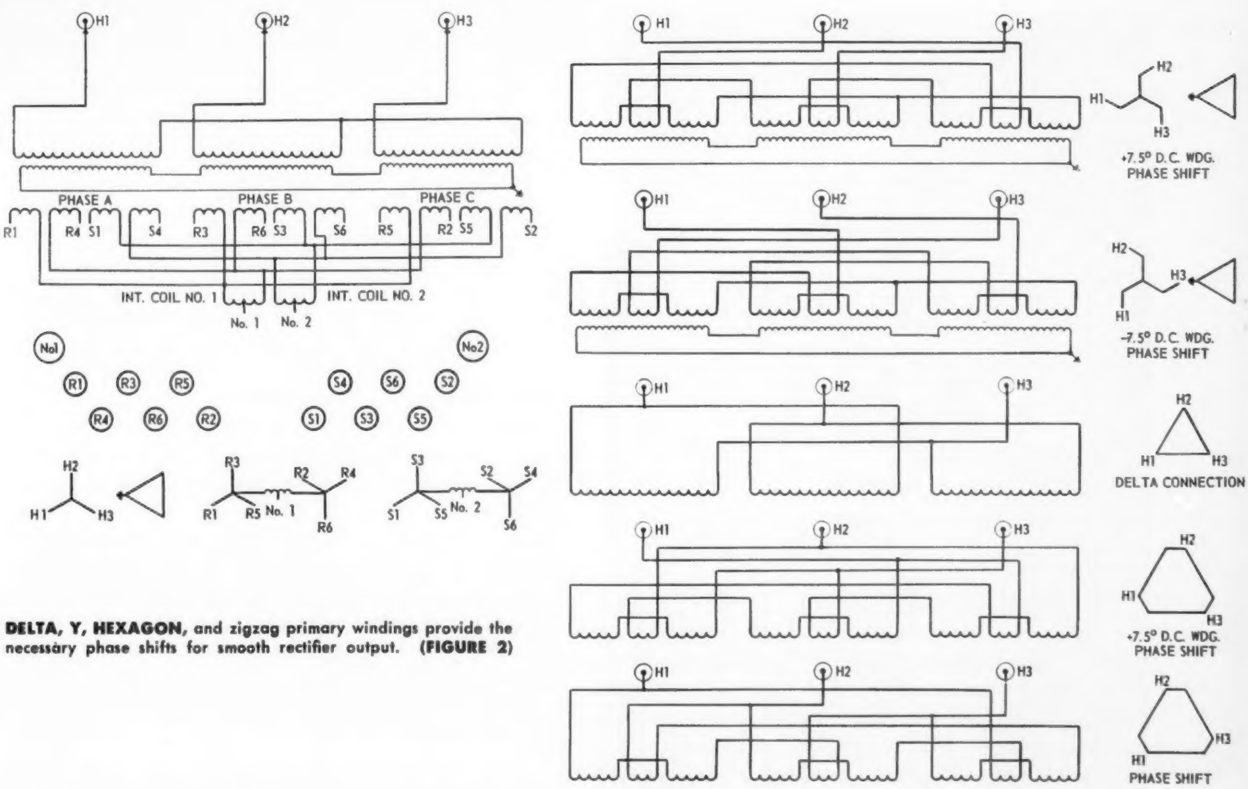
fails, causing one of the anodes to act as a cathode. All the anodes then conduct to this cathode, with the current being limited only by the transformer reactance. This imposes a short circuit on the transformer which is more severe than an alternating-current short. For proper operation of the rectifier and to balance stresses, the impedances from the primary to each leg of the secondary windings must be equal. These are general requirements for a properly designed rectifier transformer. A rectifier transformer application has other requirements which introduce a number of other special considerations.

Interphase unit improves efficiency

Three banks of eight rectifier transformers are required for the new installation. The secondary of each rectifier transformer is arranged for six-phase, parallel double-Y connection. Each secondary line bushing is connected to two single-tube rectifiers, with an anode reactor between each pair of tubes to assure proper load division. Each transformer operates two 12-tube rectifier frames. An interphase transformer, sometimes called an "absorption reactance coil," is used between each pair of Y circuits. With this connection the rectifier frame operates as two three-phase rectifiers in parallel, and each anode and transformer phase carries current for one-third of a cycle. When the interphase transformer winding is used, the rectifier transformer is utilized to greater advantage than if each phase operated only during one-sixth of a cycle, as would be the case if the neutrals of the Y's were tied together without an interphase transformer.

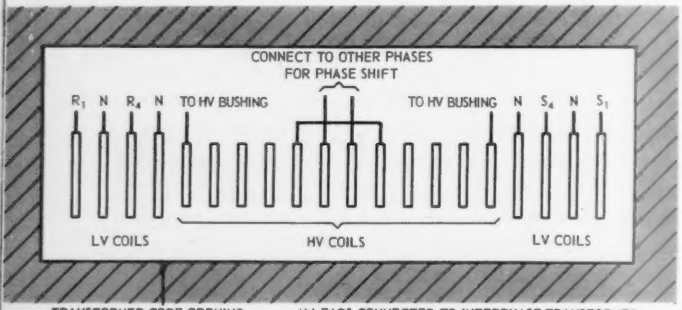
The voltage regulation of the rectifier is improved with three-phase instead of six-phase operation. The rectifier arc will carry a greater current for the same arc voltage drop as the amount of transformer regulation becomes smaller. The secondary bushings carry an rms current of 1443 amps, and numbers 1 and 2 neutral bushings carry a 5000-amp direct current with a slight ripple to excite the interphase transformer. To reduce harmonics and minimize communication interference, phase shift was introduced between all eight units in each bank. The high voltage windings were made hexagon connected, zigzag connected, delta connected and Y connected.

The eight different phase-shift connections required for each bank are as follows:



DELTA, Y, HEXAGON, and zigzag primary windings provide the necessary phase shifts for smooth rectifier output. **(FIGURE 2)**

Bank Number	Connected	Dc Winding Phase Shift
1	Delta	0°
2	Hexagon	+7.5°
3	Hexagon	+15.0°
4	Zigzag	−7.5°
5	Y	0°
6	Zigzag	+7.5°
7	Hexagon	−15°
8	Hexagon	−7.5°



COIL ARRANGEMENT for each phase provides the proper impedance for the desired rectifier operation. Transformer is also self-protected against short circuits in case of rectifier "backfire." **(FIGURE 3)**

HIGH CURRENT, low voltage requirements make necessary the winding of few turns with large conductors. **(FIGURE 4)**

Built-in phase shift reduces weight

Building phase shift into the transformers was a particular design problem. A conventional method of providing phase shift on a rectifier transformer is to mount a separate phase-shifting auxiliary transformer inside the main rectifier transformer tank. Design calculations indicated that phase shift could be built in the high voltage winding more efficiently than if separate phase-shifting autotransformers were used. Hexagon and zigzag windings in the high voltage were therefore used to provide the 7.5 and 15-degree phase shifts. Delta and Y units provided a 30-degree phase shift. The necessary extra copper required and the larger core opening increased the weight of the unit only slightly over that of a conventional design. A separate auxiliary phase shifter would have increased the weight of the transformer apparatus by 10 to 20 percent, depending on the amount of phase shift required.

Although the transformer bank was made with zigzag connections with various phase shifts, hexagon connections with various phase shifts, and delta connections and Y connections, all of the cores of the 24 units were identical in core opening size and cross section, and all 24 tanks were made exactly alike. The low voltage windings also were made the same for all 24 units. When one unit called for a plus and another a minus phase shift of the same magnitude, the high voltage windings of the two units were duplicated and the opposite phase shift was provided by reversing the terminal board connections on one of the units.

A coil arrangement with one high voltage group proved most satisfactory for obtaining the impedance required for rectifier operation and self-protection of the transformer. It also eliminated any problems of making long series connections with the bulky low voltage conductor.

Because of the complexity and number of connections to bushings, the transformers are suspended from the covers by four bolts, thus keeping all connections to the bushings intact when tanking and untanking the unit. Structural end frames clamped together with suitable bolts absorb the short-circuit forces, which are predominantly axial to the coil stack.

Transformer is water cooled

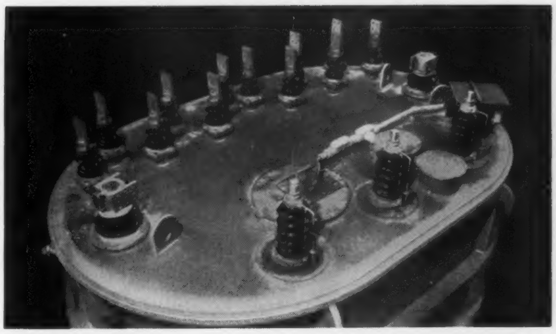
Because of the availability of cooling water at the site, water-cooled transformers (Class OW) were used. Rectifier transformers, unlike the majority of power transformers, operate continuously at maximum load, and are usually designed for a 45 C instead of 55 C temperature rise. To facilitate winding of the cooling coils, the transformer tanks were made with rounded ends. The 1¼-inch copper tubing was wound to fit inside the tank. To minimize the pressure drop through the tubing and keep the pressure at an acceptable level, several parallel circuits were provided. Water flow alarm indicators were provided for each circuit.

A positive pressure inert-gas system protects the transformer oil and insulation from moisture contamination.

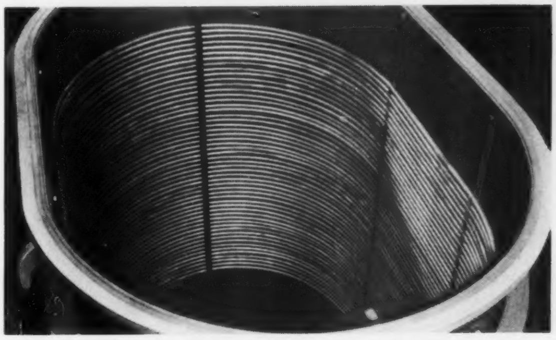
To facilitate installing the transformers, all auxiliary and alarm leads were brought to a split junction box. Splitting the junction box enables the transformer to be moved without disturbing the transformer wiring or the permanent conduit installation. The inert-gas cabinet and split junction box were made integral to simplify the conduit arrangement.

Twelve 3-kv surge arresters were provided on each transformer, one for each anode bushing, to protect the transformer from the surges encountered in rectifier operation. To connect the bushings to the overhead aluminum bus, laminated flexible jumpers were used. The increased resistance to corrosion of laminations over braid was a factor in choosing laminated jumpers for the installation.

The 24 rectifier transformers are a good example of how an elementary form of mass production can be used to advantage even on a large transformer, which is usually a custom-made item. These three banks of eight transformers will each be easily installed and economically maintained, since they have many interchangeable parts. The installation is unique in that these rectifier transformers are physically the same but electrically different.

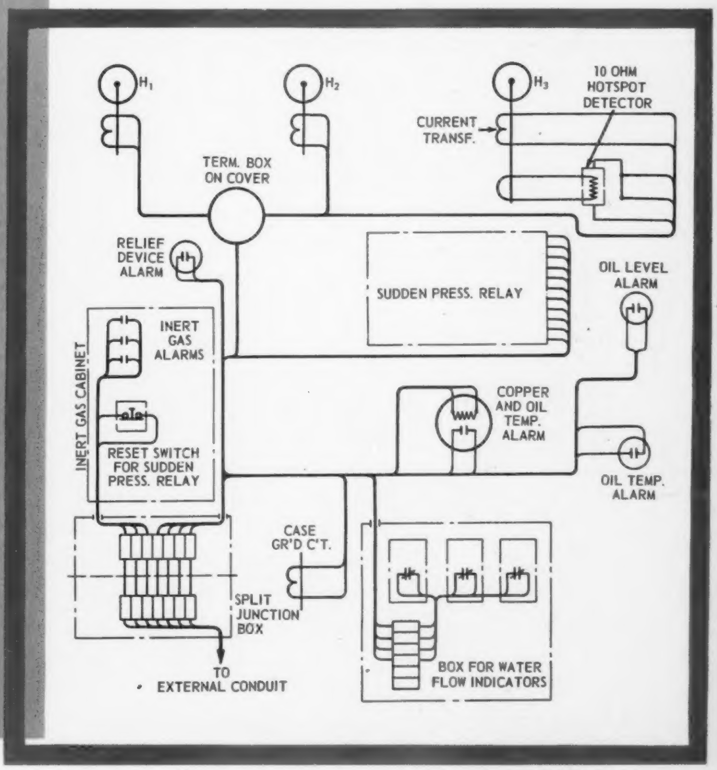


COVER BUSHINGS are arranged for convenient connections. Bushing terminals will be flexibly connected to overhead bus. **(FIGURE 6)**



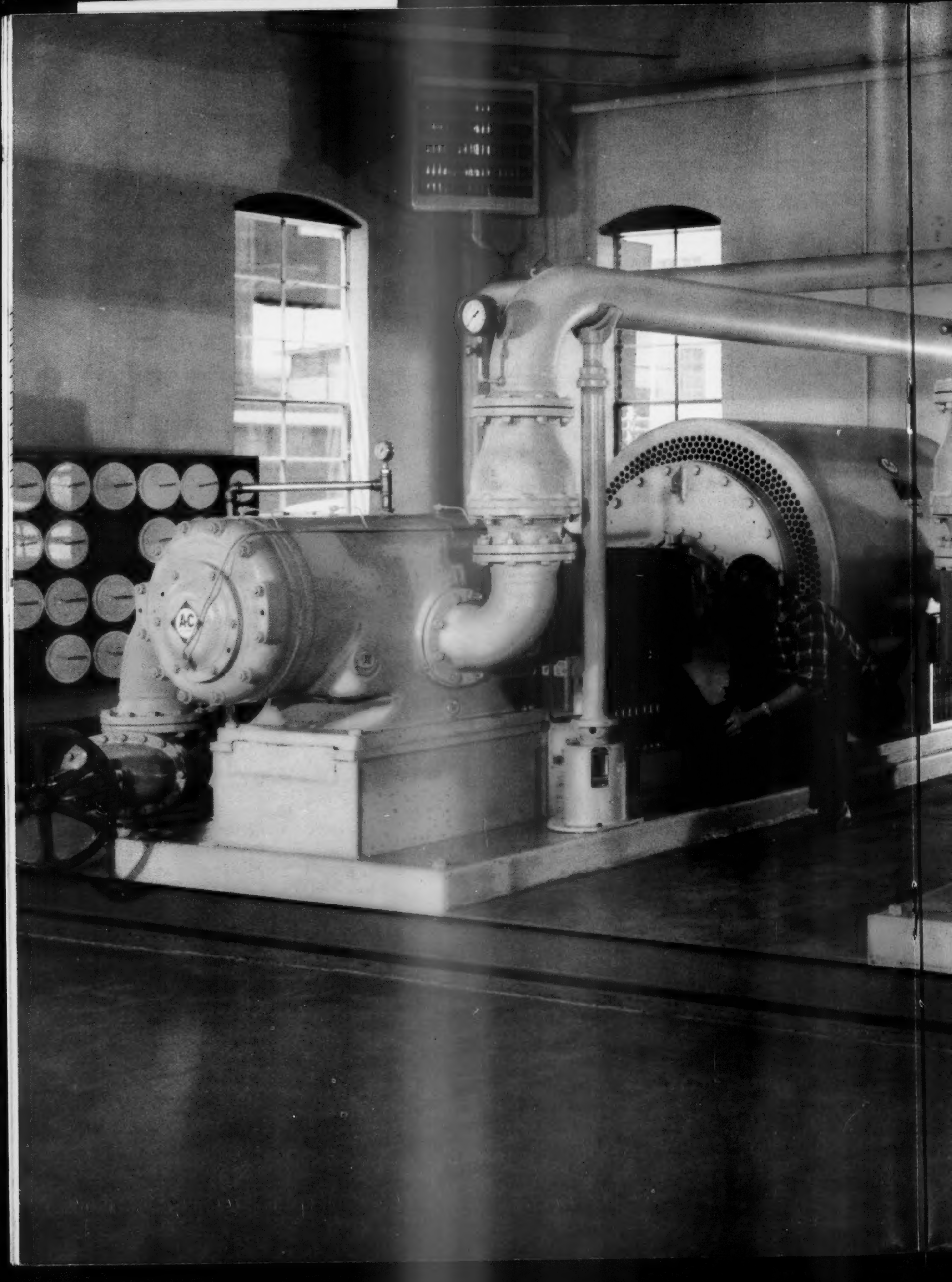
ECONOMICS DECIDED in favor of using water cooling coils because a convenient supply of transformer cooling water is available. **(FIG. 7)**

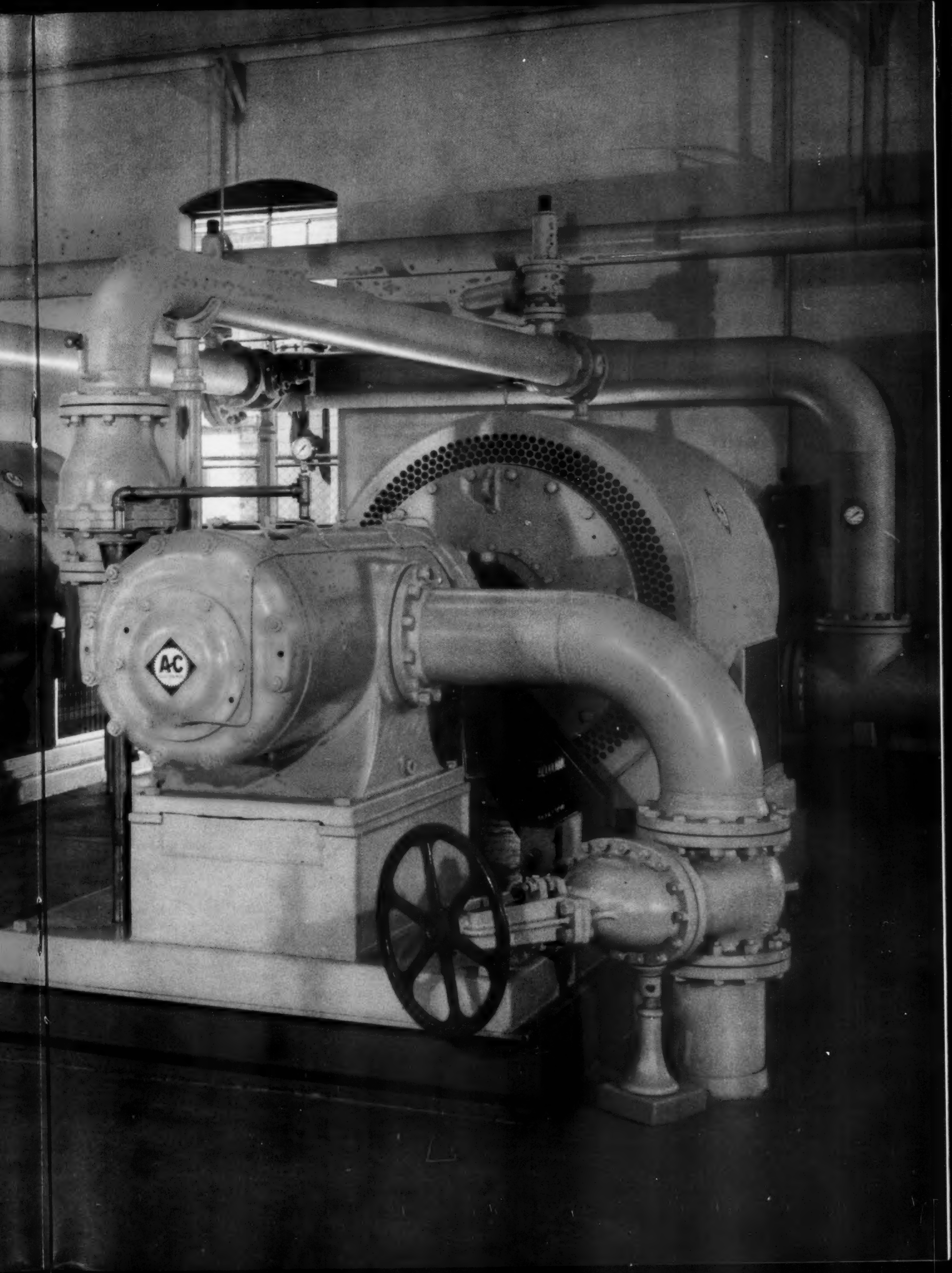
THREE-PHASE INPUT cables are connected to bushings at the high voltage side of the transformer. See vector diagrams and secondary connections shown in Figure 2. **(FIGURE 5)**



CONTROL and alarm leads terminate in split junction box. **(FIGURE 8)**

NATURAL GAS and propane-air gas are automatically proportioned by ratio control to any BTU level at a central Wisconsin gas utility. Standard rotary compressors, driven by 250-hp, explosion-proof, tube-type induction motors, furnish stand-by capacity for propane peak shaving when demand exceeds natural gas pipeline quotas. Each compressor is rated at 106,000 cubic feet per hour.
Allis-Chalmers Staff Photo by Frank Hart.

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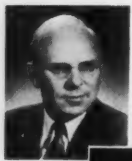
APPLYING *CAPACITORS* AT MOTOR TERMINALS

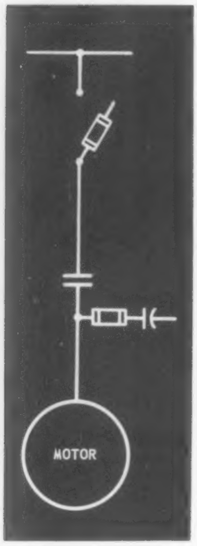


by **R. C. MOORE**
Motor and Generator Dept.
and
W. E. SCHWARTZBURG
Electrical Application Dept.
Allis-Chalmers Mfg. Co.

There is a maximum safe capacitive reactance that may be applied to induction motors for power-factor correction. Here is how to find this value.

LIGHTLY LOADED SQUIRREL-CAGE MOTORS often cause power-factor problems in industrial plants. A simple method of correcting this condition is to install static capacitors at the motor terminals. However, since the capacitors are usually switched with the motor, as shown in Figure 1, the size of the capacitor bank must be carefully selected to (1) avoid excessive voltage and (2) limit transient currents and torques. The voltage problem is caused by the capacitors supplying excitation current in excess of normal when the motor is disconnected from the line. High transient current and torque may result if the line switch is reclosed when there is residual voltage on the motor side of the switch.

Any induction motor may become a generator when disconnected from the line if there is a sufficient source of magnetizing kilovars and the shaft is driven by the connected load. Normally, when the starting contactor is opened, the source of excitation is removed and the current rapidly decays to zero. However, when enough capacitors are connected to the motor terminals, they can supply the magnetizing current after the line switch is opened. The motor can generate a voltage while the rotor



CAPACITORS for induction motors are usually connected on the motor side of the starter and are switched with the motor. Excessive capacitance can cause transient torque and voltage problems when the motor is disconnected. **(FIG. 1)**

is driven above a certain critical speed by the inertia of the connected rotating load. The magnitude of this voltage depends upon the capacitance, the saturation curve and the speed of the motor. If too great a capacitance is used, the voltage can reach values which may damage the machine's insulation. This condition can occur when the applied capacitor kvar equals or exceeds the motor magnetizing kvar at normal voltage and frequency.

Capacitance depends on saturation curve

It is very simple to determine the critical value of capacitance through the use of the motor's no-load saturation curve. A typical pipeline pump application using a motor rated 700 hp, 4160 volts, three phase, 60 cycles, 900 rpm can serve as an example. From the no-load saturation curve shown in Figure 2, the magnetizing current at 100 percent voltage is 21.5 amperes. Since $\text{kvar} = (I)\ (E)\ (\sqrt{3})/1000$, the magnetizing kvar becomes $(21.5)\ (4160)\ (\sqrt{3})/1000$ or 155.

The capacitance in microfarads $C = (1000)\ (\text{kvar})/(2\pi f)\ (\text{kv})^2$ or 23.75 mfd. The actual capacitive reactance in ohms is $X_c\ (\text{ohms}) = 10^6/2\pi fC$ or

at 60 cycles $X_c = 2653/C\ (\text{mfd})$

giving a value of 111.7 ohms. Assuming different values of voltage, the straight line labeled "155 kvar" can be constructed. To find the terminal voltage if 175 kvar of capacitors are used at the motor terminals, another line is constructed representing the X_c or 98.5 ohms. This capacitance results in a terminal voltage of 4950 volts when the motor is disconnected from the line. The voltage is approximately 119 percent of normal and may damage the insulation. As the speed drops a frequency is reached at which the capacitance will no longer supply sufficient magnetizing kvar to sustain this voltage.

When the motor is running at full load its power factor is 90 percent and efficiency is 94 percent. With this power factor the vector diagram of the motor with no capacitors may be constructed as shown in Figure 3*a*. This motor

draws 555 kw at full load as calculated from the equation kw = hp (.746)/eff. Similarly, the kva is 617 and the kvar of motor reactance is found to be 270. If 155 kvars of capacitance are added, this quantity may be subtracted from 270 kvar, leaving 115 kvar. The vector diagram shown in Figure 3*b* is constructed from Figure 3*a*. The power factor of the combined motor and capacitor bank is 97.9 percent. The power factor resulting from any given bank of capacitors applied to the 700-hp motor is shown in Figure 4. If correction to 100 percent power factor at 700-hp load is desired, 270 kvar must be supplied by the capacitors. Figure 2 shows that a voltage of 145 percent of normal is generated if there is no drop in motor speed.

Capacitors change motor time constant

The length of time that a motor continues to generate voltage after it has been disconnected from the line is determined by the Wk^2 of the load and motor which tend to maintain speed, the load torque which acts as a brake to reduce speed, and the motor open-circuit time constant. When capacitors are added, as shown in Figure 5, the time constant increases and consequently voltage decay is slower.

The closed rotor circuit without capacitors has the open-circuit time constant

$$T_o = \frac{X_m + X_2}{\omega\, r_2} \qquad (1)$$

where ω is 2π times the primary supply frequency. When the breaker is opened, with capacitors in the circuit, the rotor current paths are as shown. Rotor current flows through the parallel reactance combinations of $(X_1 - X_c)$ and X_m. This combination is in series with X_2, so that the reactance for the time-constant calculation is

$$X = X_2 + \frac{X_m\,(X_1 - X_c)}{X_m + X_1 - X_c} = X_2 + \frac{X_m\,(X_1 - X_c)}{X_d - X_c}$$

where $X_d = X_1 + X_m$ = synchronous reactance.

The open-circuit constant with capacitors is

$$T_o' = \frac{X}{\omega\, r_2} \qquad (2)$$

where ω is 2π times supply line frequency.

The time constant with capacitors (T_o') may be related to the time constant without capacitors (T_o).

$$\frac{T_o'}{T_o} = \frac{\text{Eq. (2)}}{\text{Eq. (1)}} = \frac{X_c - X_1}{X_c - X_d} - \frac{X_2\,X_m}{(X_m + X_2)\,(X_c - X_d)} \qquad (3)$$

This relation indicates how much the time constant without capacitors, T_o, is extended when using less capacitor kvar than the motor magnetizing kvar, at rated voltage and frequency.

Considering first the condition without capacitors, $X_c = \infty$, we may calculate from Eq. (3)

$$\frac{T_o'}{T_o} = 1 \text{ or } T_o' = T_o \text{ (an identity)}$$

The actual value T_o for the 700-hp motor may be calculated from Eq. (1)

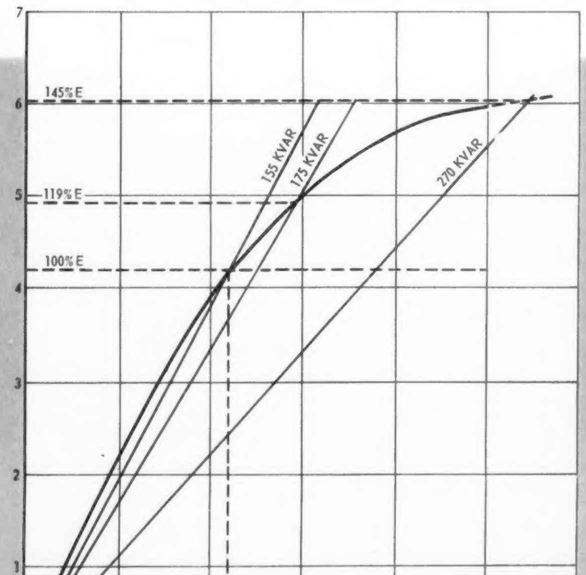
$$T_o = \frac{X_m + X_2}{\omega r_2} = \frac{111.8 + 2.67}{377 \times .45} = 0.675 \text{ seconds}$$

Figure 6 shows the voltage decay without capacitors.

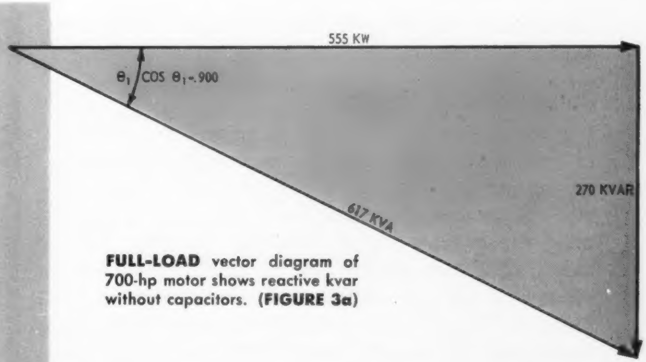
Capacitor is used to correct power factor

If capacitors are applied to the motor terminals to obtain, say, 97 percent power factor at 700 hp, then from Figure 4, 132 kvar will be required (motor magnetizing kvar at rated voltage and frequency is 155). For 132 kvar of capacitive corrections, X_c is calculated to be 131 ohms. From Eq. (3)

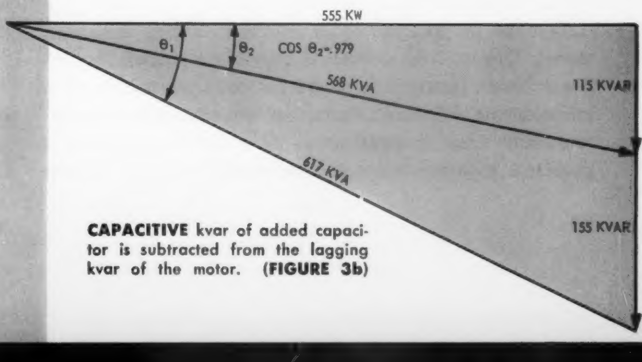
$$\frac{T_o'}{T_o} = \frac{131 - 2.67}{131 - 112} - \frac{2.67 \times 112}{114.67\,(131 - 112)} = 6.61$$



NO-LOAD SATURATION CURVE provides the key to critical value of capacitance that may be used at motor terminals. **(FIGURE 2)**



FULL-LOAD vector diagram of 700-hp motor shows reactive kvar without capacitors. **(FIGURE 3a)**



CAPACITIVE kvar of added capacitor is subtracted from the lagging kvar of the motor. **(FIGURE 3b)**

The open-circuit time constant with capacitors is 6.61 times the open-circuit time constant without capacitors.

The actual time constant with capacitors is

$$T_o' = 0.675 \times 6.61 = 4.45 \text{ seconds}$$

The residual voltage decay employing the time constant of 4.45 seconds is shown in Figure 6.

The calculated values of open-circuit time constants are the maximum values if no allowance is made for reduction of motor speed. High inertia drives such as unloaded chippers may, for all practical purposes, sustain the combined unit speed for several seconds, which may be longer than the open-circuit time constant. With a slow voltage decay, the motor may be re-energized before the residual voltage drops to a safe value.

If the inertia of the connected load is not great and the speed of the motor drops rapidly after the breaker opens, the residual voltage decay is faster than with a less rapid drop in speed, as with a high inertia driven load.

Capacitor values can be too large

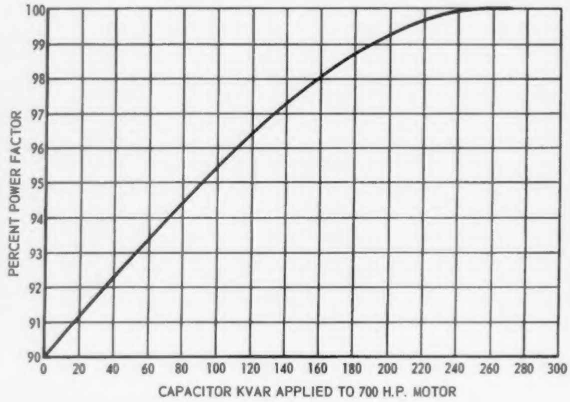
Equation 3 indicates that T_o'/T_o becomes infinite when X_c equals X_d. This occurs when the motor no-load magnetizing kvar is equal to the capacitor kvar being used, at rated voltage and frequency of the motor. A greater value of capacitance will cause the motor terminal voltage to rise when the line breaker is opened. The value of the voltage rise may be obtained from the curve shown in Figure 2, assuming the motor speed remains constant.

The 270 kvar of capacitors of Figure 4 will provide a combined motor-capacitor power factor of 100 percent at 700-hp motor load. When the breaker is opened, the voltage will rise to 145 percent of normal, as shown in Figure 2, if there is no drop in motor speed. The magnitude of the motor terminal voltage from Figure 2 will be the maximum expected value with constant motor speed resulting from a high inertia load. If the motor speed drops after the breaker is opened, the motor terminal voltage will also drop. In the absence of information on inertia values, the use of Figure 2 is suggested for determination of terminal voltage.

Reconnection is delayed

A common practice in the power generation industry is to delay reconnection until the residual terminal voltage has decayed to 25 percent of normal value. Higher residual voltage than 25 percent may be tolerated at transfer using the inphase transfer principle. Inphase transfer means, of course, reapplication of incoming voltage in phase with the residual voltage. Inphase switching, although not widely used, has been the subject of research and exploratory testing in several AIEE publications.

The nameplate data alone will not help determine the correct size of capacitor to be used with a large induction motor. The no-load saturation curve, the efficiencies and power factor obtained from the motor manufacturer, plus a few simple slide rule calculations will establish the maximum safe value of capacitance. This caution may obviate problems with insulation and transient current or torque.



COMBINED POWER FACTOR of motor and capacitor bank of the 700-hp motor with various capacitor values is given. **(FIGURE 4)**

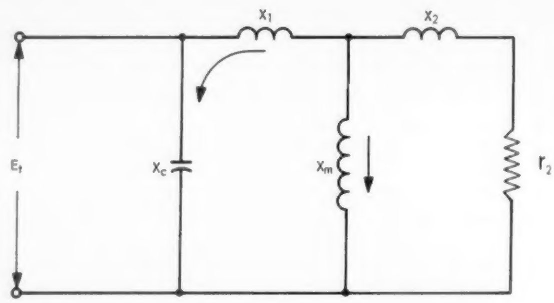
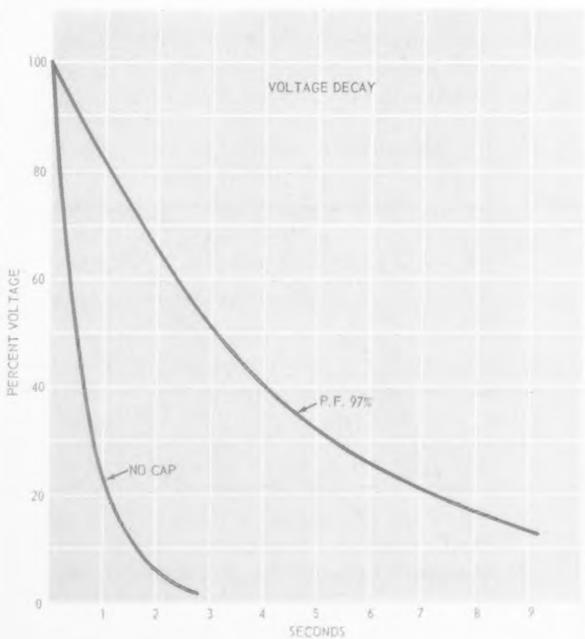
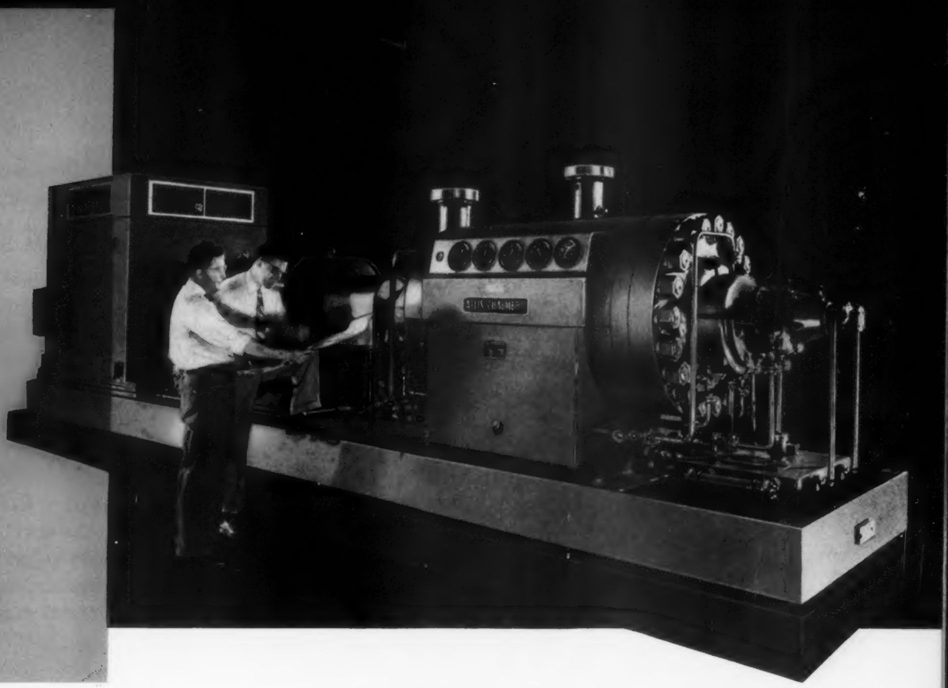


DIAGRAM with capacitors added shows paths of transient current flow when the line breaker is opened. **(FIGURE 5)**



VOLTAGE DECAY is longer when capacitors are added at the motor terminals than without capacitors. When the motor is reconnected immediately after opening, voltage decay rate must be considered. **(FIGURE 6)**

matching the boiler feed pump TO YOUR JOB



TYPICAL BARREL-TYPE boiler feed pump and variable-speed fluid drive, coupled to induction motor, are built to serve the high-capacity boilers in modern power plants.

by **R. A. MILLER**
Centrifugal Pump Dept.
Allis-Chalmers Mfg. Co.

Here's how pumps are selected to supply the power boilers for power companies and industry at large. Dependability and low maintenance are essential.

STEAM PRESSURE DRIVES the turbine-generators in conventional power stations as well as in the present nuclear plant installations. The source of today's tremendous steam requirements are power boilers supplied by boiler feed pumps. These pumps must serve all of the boilers' needs to meet the power requirements of electric utilities and industry.

The modern boiler feed pump produces the proper volume of water at the correct pressure and can be controlled to satisfy a varying rate of boiler steam production. When it is realized that the modern boiler has approximately only 12 minutes or less total water supply, the supplying of high pressures and large volumes of water is a critical consideration. The pump must reliably furnish boiler make-up to correspond with a variable steaming rate, within very close limits. Consequently, the type of boiler feed pump selected will be governed by ease of control as well as by cost, efficiency, space occupied and maintenance. Figure 1 shows schematically a typical arrangement of the components in a power station.

Wide range of capacities are served

Low, intermediate, and high pressure boilers tend to classify boiler feed pump applications. There is considerable group overlapping, but low pressure heating and industrial process boilers usually operate at pressures of 225 psi or less with feed water at 240 F or less.

For very small capacities of from 10,000 to 15,000 pounds per hour or less, direct-acting steam piston pumps have been and still are being used. They are efficient and can be controlled reasonably well by varying the steam flow to the pumps. Variable-stroke motor-driven pumps are also used, but control is a problem despite their high efficiency.

Centrifugal pumps, like the boilers themselves, tend to approach constant pressure with varying volume. Moreover, a centrifugal pump is much less expensive and requires much less maintenance than a piston pump of comparable capacity. Centrifugal pumps are easily controlled by throttling the discharge and use efficient, lower cost, high speed motor drives.

In the lower pressure — lower temperature classification, centrifugal pumps are made with less expensive standard materials, such as cast-iron casings and iron or bronze fittings. Antifriction ball bearings also tend to lower costs.

The centrifugal pump is inefficient at low capacities, in the area of 15 to 20 percent, as compared to 85 to 95 percent for a comparable size piston pump. These capacities are in the low 10,000 to 15,000 pounds per hour class. When a centrifugal pump operates at 3600 rpm, leakage through the running clearance (0.10 to 0.15 inch) may exceed pump output, resulting in relatively low efficiency. At larger volumes running clearance is the same and leakage is constant, but it is a smaller portion of total output. Consequently higher efficiencies are obtained. When volumes approach 400,000 to 500,000 pounds per hour, efficiencies up to approximately 80 percent may be expected. Figure 2 shows running clearance.

In spite of low efficiencies at low capacities, centrifugal pumps are often used because of the ease of control. A throttling valve, controlled by a float or similar device sensitive to water level, is all that is required.

A multi-stage centrifugal boiler feed pump is not always required. In the low pressure classification of 225 psig or less, single-stage pumps are often adequate. Sometimes single-stage pumps may be a few percent less efficient than a comparable capacity multi-stage pump; however, there may be a saving of several hundred dollars in the first cost of the single-stage pump. Such a saving will far outweigh the small increase in multi-stage pump efficiency.

Many operators prefer split-case, two-bearing pumps because of the low maintenance factor. The less expensive integral motor and pump combination should also be considered, especially for the industrial applications of heavy 8-hour service and 16-hour light duty. A spare duplicate unit can be purchased at the overall cost of a pump baseplate motor and coupling of the separately mounted type. No special materials are generally required, but stainless steel sleeves and metallic packing are desirable. Occasionally mechanical seals are specified and are becoming more popular.

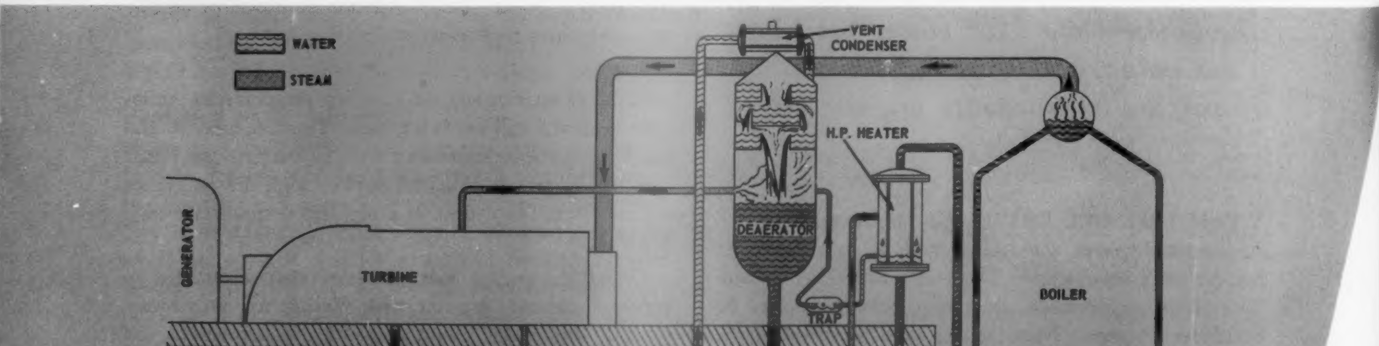
Special techniques and materials advised

The intermediate pressure classification includes industrial plants, municipal power stations and smaller utilities up to and including 22,000-kw stations. The pressure range is from 225 to 850 psig. Multi-stage, horizontal split-case centrifugal pumps satisfactorily supply boilers in this group. Split casings are used successfully for these applications, even though pressures may approach 1200 psig. Figure 3 shows the vertical and horizontal split-case pump.

Since pressures are higher and more radial thrust is imposed on the shaft, staggered and double volutes are used for radial balance. Axial balance requires double-suction in-line or single-suction back-to-back impellers. Figures 4, 5 and 6 show typical arrangements.

Higher temperature operation requires certain modifications, such as water-cooled stuffing boxes, smothering or quenching glands, water-cooled bearings, or centerline supports. For higher pressures, sleeve bearings with Kingsbury thrust bearings are often specified because of higher bearing loads. This combination usually requires pressure lubrication with an oil cooler and reservoir.

In the lower temperature range of the intermediate classification, cast-iron casings, bronze fittings and ball bearings are usually satisfactory. Since any chemical reaction on metal will be accelerated in the higher temperature range — 250 F or higher — some form of stainless steel for wearing parts or wetted parts will often be specified. A 4 to 6 percent chrome steel casing and 12 to 14 percent chrome fittings are usually specified at temperatures above 280 F. The pH value of the water is a definite criterion of material requirements, but this alone is not sufficient to make a final decision.



Boiler feed water is usually kept at a pH above 7.0. At temperatures below 250 F with a pH of 7 to 8½, cast-iron casings and bronze fittings are often adequate. However, for stations with a very low make-up rate, it may be necessary to use some stainless steel parts. The continual distillation in the boiler removes salts from solution and leaves the water with a strong tendency to attack metal surfaces. This is called "hungry water." Stainless steel parts are recommended because they do not readily react with the hot distilled water.

Barrel pumps designed for high pressure

Boilers operating at pressures over 850 psig are considered to be high pressure boilers. At working pressures of approximately 1250 psig the internal pressure in a split-case centrifugal pump begins to stretch and distort the casing. Impeller diameters get larger; flanges are farther from the shaft centerline. Even though the flanges can be held, the casing tends to spread apart near the shaft at the diaphram between stages. Ribs cast integral with the casing help to reduce distortion, but they too reach a limit and are a further detriment when pumping hot water, since there is unequal expansion between light and heavy sections.

The double-casing or barrel-type pump solves the high pressure design problem. Hydraulically there is no difference in the impellers, but full discharge pressure released in the space between the two cases provides a hydraulic clamp and puts the inner casing under compression. Only the last stage discharge has an equal pressure; all other stages are at lower pressure. Since materials are much stronger in compression, the section of the inner casing can be made thinner. Sections are symmetrical because there are no feet or nozzles. Since the inner case is made light in weight, better materials can be used without increasing the cost unreasonably. Figure 7 shows how the barrel construction compares to the split-case type. However, a barrel pump costs considerably more than a split-case pump because of the double casing. More parts are required and special seals are needed between inner and outer casings. More dismantling space is required because the inner casing must be removed from the end of the barrel. The barrel construction solves only the bolting problem resulting from high pressures; it adds nothing hydraulically. A split-case pump, such as the one shown in Figure 8, should be used except when the operating pressure becomes excessive.

On large-size pumps an auxiliary motor-driven oil pump is sometimes used in addition to the shaft-driven oil pump. This insures oiling protection during start-up and shut-down, as well as in the event of main oil pump failure. A pressure switch actuates the auxiliary motor-driven pump. Electrical interlocks between auxiliary starter and main starter insure that the auxiliary oil pump is running before the main pump motor can be started.

Many factors included in pump sizing

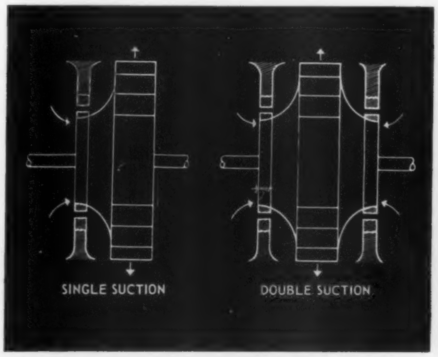
The two distinct fields in boiler feed pump sizing are industrial and power generation. Industrial boilers are often purchased in batteries because of the flexibility needed for daily and seasonal load changes. One or two pumps might serve four to six boilers, with pump sizing taking future plant expansion into consideration.

BOILER FEED PUMPS have substantial horsepower requirements, since they pump in all the boiler feed water against boiler pressure. The high pressure heater should be located as high as possible to permit using the most efficient pump, because an increase of only a few percent efficiency represents a large saving in horsepower. It may be economically feasible to raise an existing heater when replacing a boiler feed pump.

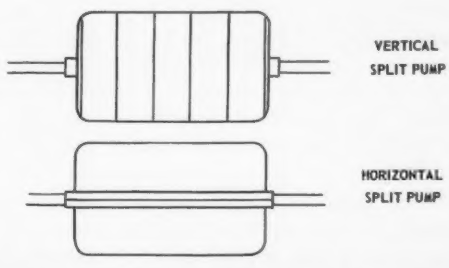
The arrangement of pumps in a power plant may have critical suction considerations. Each pump handles condensed steam at the saturation point corresponding to the temperature within the vessel.

According to the diagram, the condenser cannot be raised, causing low suction head at the condensate pump. Suction head could be improved by excavating to lower the pump, but that would create an unsightly pit. A vertical pump submerged in a tank sunk in the floor below the condenser will provide greater suction head. This method is especially desirable when pumping at higher pressures. An increased pump efficiency would offset the increased installation cost.

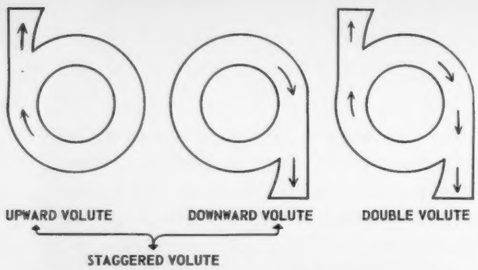
The heater drain pump often can be assisted by raising the low pressure heater. Such action is usually not necessary, since the volume handled is relatively low. **(FIG. 1)**



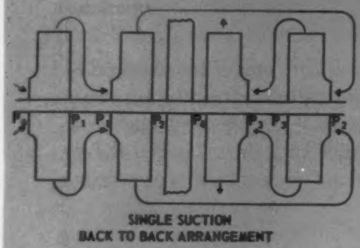
CLEARANCE LEAKAGE is greater with double-ring than with a single-ring impeller, but double-suction impeller will handle more lift. **(FIGURE 2)**



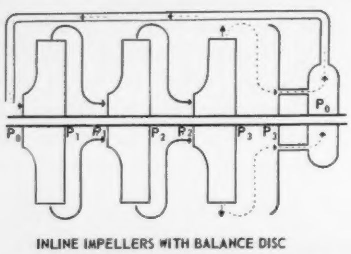
PUMPS are either horizontally or vertically split, depending on design and fabrication preferences. **(FIGURE 3)**



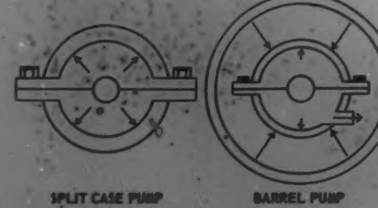
SINGLE VOLUTE produces radially unbalanced reaction on pump shafts. Staggered or double volutes offset shaft reaction to improve operation. **(FIGURE 4)**



BACK-TO-BACK arrangement offsets axial thrust produced by single-suction impellers. **(FIGURE 5)**



BALANCE DISC design corrects for axial unbalance of inline impellers. **(FIG. 6)**



HIGH PRESSURES cause split pump casing to distort. Barrel allows discharge pressure to act as hydraulic clamp. **(FIGURE 7)**

Pump loads are not continuous and efficiency is not the prime consideration. The most efficient pump for a desired rating will be selected, but the rating may be far from the average present-day load. However, excessive pump size is not required, but too small a pump should not be selected. Heating boilers generally will not require oversize boiler feed pumps because the load is more accurately predicted.

Power generation boilers are sized for the generator capability. Duty will be reasonably constant, and everything in the station will be sized for maximum efficiency for the planned installation. The following table shows typical factors that govern boiler feed pump selection.

Boiler rating	100,000	lb per hour
Leakage and blowdown	5,000	lb per hour
Boiler feed pump rating	105,000	lb per hour
Design pressure at boiler drum	650	psig
Safety valve setting plus	25	psig
	675	psig
Boiler drum elevation	15	psig
Pressure drop through economizer	20	psig
Pressure drop through feed water regulator	30	psig
Pipe friction	10	psig
Total	750	psig
Allowance for wear or error	30	psig
Rating boiler feed pump pressure	780	psig

The reliability and extremely low rate of wear of boiler feed pumps indicate that they should not be oversized any more than is necessary to protect the boiler in an emergency. Any excess capacity above that needed for a boiler emergency results in a constant loss in brake horsepower. The feed-water regulator must therefore throttle the useless excess and perhaps the extra pressure differential will make regulator operation sluggish.

Pump control depends on type of drive

Most boiler feed pumps handle feed water at the saturation temperature, that is, the boiling point corresponding to that pressure. The pumping action of centrifugal boiler feed pumps lowers the pressure at the suction inlet, and since a pump adds velocity at the outlet, it will reduce the pressure a like amount at the suction. Therefore a margin in feet of head over and above the inlet pressure reduction must be provided. If a pump reduces the pressure 15 feet, a static elevation of more than 15 feet, plus a comfortable safety margin, should be provided for quiet operation. Poor suction conditions often make pump operation noisy.

Some type of control is required to match the pump output to the boiler demand. An excess pressure control is usually used in the supply line of a turbine drive. With this control a diaphragm is attached to the turbine throttle valve. Pump pressure is connected to the top of the diaphragm and boiler pressure to the bottom, with a coil spring added to the bottom to provide a differential.

As the pump pressure builds up and exceeds the boiler pressure plus the force of the added spring, the valve starts to close, throttling the steam supply and slowing the turbine to the exact speed required to maintain the differential. The result is a saving of brake horsepower at partial loads, providing a constant differential across the feed-water regulator.

If a battery of boilers is fed by one pump, it is sometimes advantageous to use a constant pressure regulator. This arrangement is similar to the excess pressure control, but uses only a heavy spring on the bottom of the dia-

phragm. Therefore, constant pressure is available to feed the boilers regardless of the load on each boiler.

With constant speed motor drives a constant pressure governor may be used to throttle out some of the excess head provided by the pump. The governor lowers the differential across the feed-water regulator to improve regulator sensitivity, which is advantageous if the pump has a steep slope head curve.

Electric motor drives are most commonly used with boiler feed pumps because of reasonable cost and high efficiency. Two-pole, squirrel-cage open drip-proof motors are adequate, except in hazardous locations. It is not necessary to oversize motors, since pumps are rated for maximum conditions which cannot be exceeded unless extra boiler capacity is added.

Motor drives from 5 to 100 hp are used to supply boilers in the low pressure heating and industrial processes. Usually pumps in these applications are rated at full boiler capacity. Since there is little possibility of exceeding the pump rating, the motor need not be sized beyond the rated brake horsepower. In practice, full-capacity pumps rarely operate at their rating, making it quite common to use the motor service factor to reach the rated brake horsepower. If the brake horsepower is 83, a 75-hp open motor with silicone-rubber insulation should be enough protection even for conservative operators.

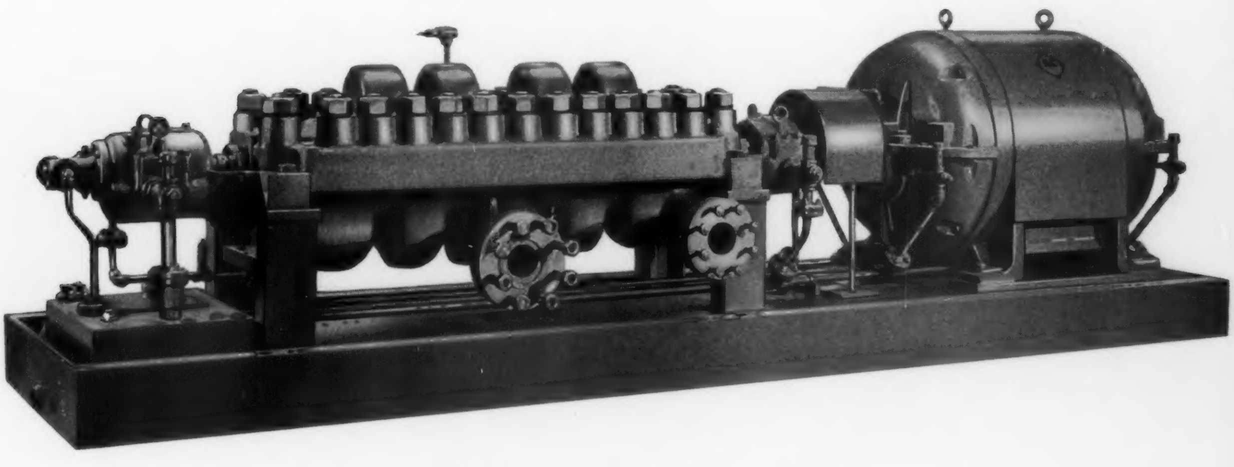
In the intermediate pressure range, motor drives are sized from 100 to 800 hp. Motor drives are sized to the pump rating, taking the motor service factor into account to meet maximum pump brake horsepower. Half-capacity pumps are sometimes chosen by utilities and industry when the boiler load will be low much of the time. As an example, at a 287 brake horsepower pump requirement a 300-hp standard 40 C rise open motor would normally be used. However, a lower cost 250-hp motor with silicone-rubber insulation and 60 C rise will carry a 287 brake horsepower load without injurious effects.

Turbine drives are necessary for starting up in plants which do not have interconnection with other transmission systems. At diminishing steam turbine loads the steam consumption per horsepower increases. Unless process work can absorb the increase, the excess steam is wasted. The turbine may not be efficient at partial loads, but a saving in horsepower can sometimes make up for reduced operating efficiencies. However, turbines are more expensive than motors of comparable rating and also require more adjustment and repair.

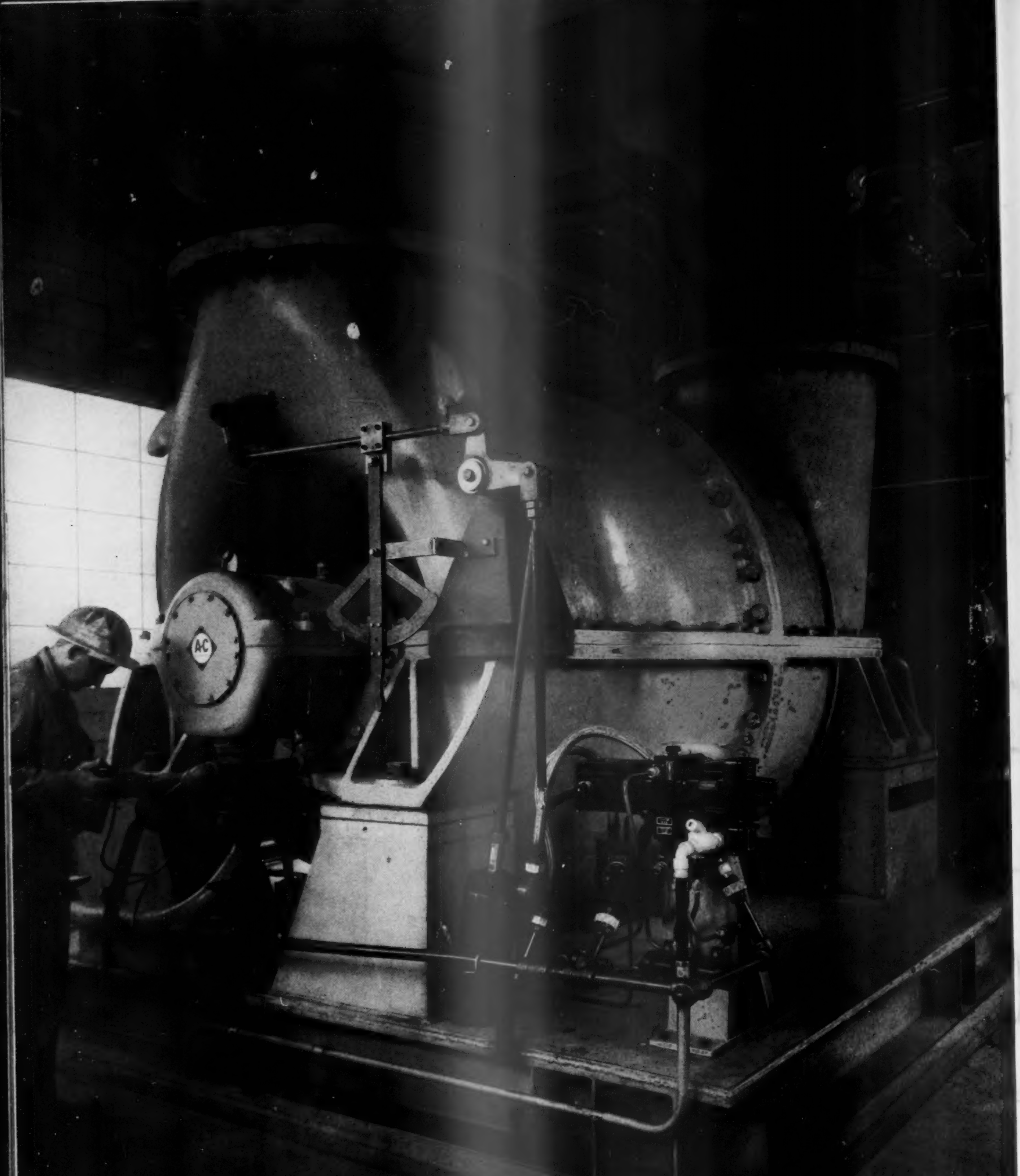
Magnetic or fluid drive variable-speed controls for motor-driven pumps are rather expensive; therefore, the horsepower savings must be substantial to justify their cost. They are rarely used for boiler feed work at less than 500 hp. Wound-rotor or direct-current motors are also seldom used as boiler feed pump drives.

The most common boiler feed pump drive is a direct-connected open squirrel-cage motor with an across-the-line starter. Occasionally reduced-voltage starters are used. No special controls or expensive equipment is required, and many installations operate for 5 to 10 years with no attention beyond adjusting or replacing packing.

The highly efficient boiler feed pump makes an effective contribution toward lower operating costs. Today all that is required is proper selection, good installation, occasional lubrication, and the pump will be a dependable servant for many years.



TYPICAL SPLIT-CASE PUMP has staggered volutes for radial balance and back-to-back impellers for axial balance. **(FIG. 8)**

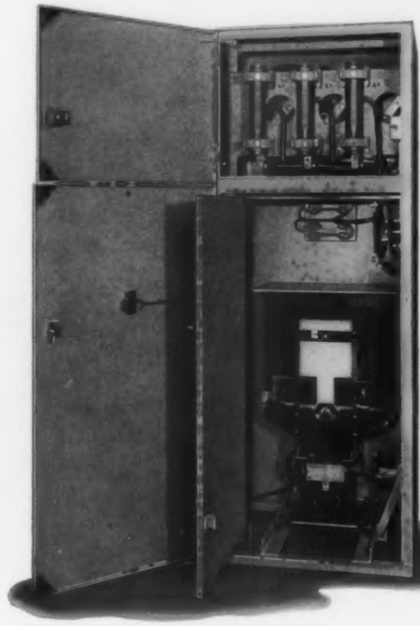


FOUR-STAGE CENTRIFUGAL COMPRESSOR furnishes large volume of air necessary to regenerate spent catalyst in a midwestern oil refinery. The carbon, deposited on the catalyst during cracking of the hydrocarbon charge, is burned off to regenerate the catalyst. A catalyst greatly aids the conversion of non-gasoline hydrocarbons into desirable gasoline components. The compressor, operating at 3650 rpm and rated at 53,000 cfm with a discharge pressure of 43.4 psia, is driven by a 5500-hp induction motor.

Allis-Chalmers Staff Photo by J. E. Gossock

OIL CONTACTOR in new front-access starter.

OIL or AIR



AIR CONTACTOR in new front-access starter.

contactors for medium voltage control

by **H. A. WRIGHT**
Control Department
Allis-Chalmers Mfg. Co.

New, compact oil contactor designs bring an old question back to life.

WHETHER OIL-IMMERSED or air contactors should be used on 2 to 5-kv motors is a question that cannot be answered without a complete knowledge of the application and the environmental conditions.

Air contactors and breakers came into the picture in the early 1940's. Before that time only oil-immersed equipment was available. During the war years, while plants grew and distribution system capacity was increased, oil switchgear could not be readily replaced, even though some breaker ratings were below the system short-circuit capacity. While properly applied oil circuit breakers were thoroughly reliable, air circuit breakers were introduced about this time because they were easier to maintain and provided faster interruption. Oil switchgear was replaced with new air gear of proper capacity.

The big drive for air switchgear also carried over to the industrial control field. As a result, some prejudice was attached to oil and in many cases air contactors were used where perhaps oil should have been considered, thus discouraging the development of new oil-immersed contactors. Development since the war has been aimed at providing reliable air contactors with a maximum rating of 400 amps, 5 kv, 50,000 kva in a small package.

The petroleum industry had a requirement for medium voltage control to be installed in hazardous gas atmospheres to meet NEC Class 1 Group D, Division 1 and 2 standards. Oil-immersed equipment was the only practical answer to these applications. Little choice in size and rating had been available, however, since development priority was allocated to air equipment. The industry therefore requested that a new oil contactor be developed having the same maximum rating as the popular air contactor and housed in a small tank which could be mounted in a normal cubicle with fuses. Such a contactor, shown in Figure 1, has now been developed and is available. Figure 2 shows the comparable air contactor.

Oil contactor construction

The contactor itself is completely immersed in oil. The creepage to ground and between phases is less than in air. The principle of arc interruption is entirely different from air interruption. When the contacts part in oil an arc is drawn and heat from the arc causes a gaseous bubble to form under the oil. Since the bubble is lighter than oil,

it begins to rise vertically. Its size depends upon the arc energy to be dissipated. The sudden expansion is transmitted hydrostatically to the tank as a pressure wave. The heat within the bubble is absorbed by the oil, causing a small amount of the oil to break down and form carbon, which is an oil contaminant.

Air contactor construction

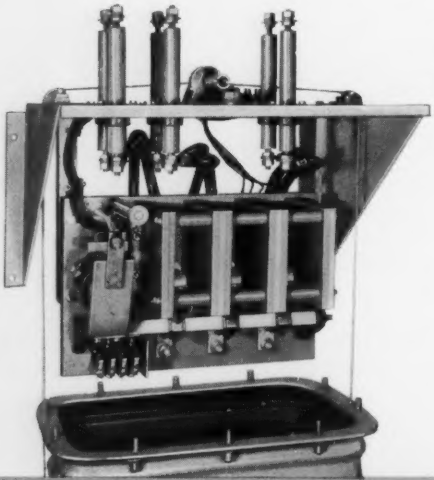
The movable and stationary contacts of the air contactor are held by insulated supports. Electrical creepage across clean, dry non-tracking insulators must be at least 3½ inches. The through-air spacing of live parts of opposite polarity must be 2 inches. In order to obtain the proper insulation level, most air contactors are of open design and have few flat surfaces to collect contaminants, such as dust and moisture. Since the arc energy must be dissipated in air, the critical design problem is arc extension in the blowout structure and arc chutes. Further, the ionized gases must be dissipated within the enclosure. For this reason the control components must be mounted away from the gas blast area.

Application determines contactor type

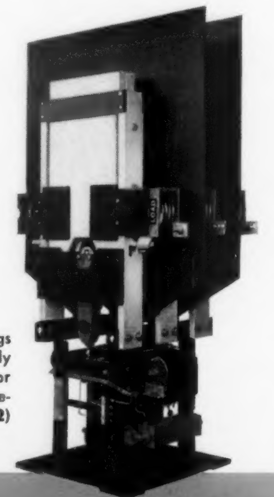
For highly repetitive service air contactors are preferred, but for hazardous atmospheres oil contactors are recommended. Since an oil contactor is now available having the identical rating of the air contactor, there are many applications where either air or oil contactors may be used. Until now, only air contactors have been available in the new, fused front-access starters such as might be applied to a 1000-hp, 4160-volt synchronous motor driving a cement plant grinding mill. There was no choice for this application even though the dust condition was severe. Here oil might be considered if a means were provided for positioning the mill, as with an incher. However, there are some installations where the grinding mill is jogged for positioning. In such cases air is preferred, since oil is not recommended for jogging duty.

Oil contactors might be selected for a pump in a paper mill where the atmosphere may be contaminated with corrosive elements plus water vapor. If the pump operates for days without stopping, oil should be considered. However, if this pump is operated on two-wire control from a pressure switch, air is a better choice, since the duty may be repetitive.

The advent of a new oil contactor in a size and rating corresponding to air contactors opens new possibilities for reliable control in areas where air contactors were previously the only choice.



NEW OIL CONTACTOR with a maximum rating of 400 amps, 5 kv, 50,000 kva interrupting capacity and requiring only 30 gallons of oil was designed for Class 1 Group D, Divisions 1 and 2 hazardous locations. It may also be used in contaminated atmospheres or where dust is a problem. **(FIG. 1)**



AIR CONTACTOR with the same maximum ratings has proven its value in applications requiring highly repetitive duty. Since it is primarily designed for normal operating conditions, the contactor is widely used in all types of industries. **(FIGURE 2)**

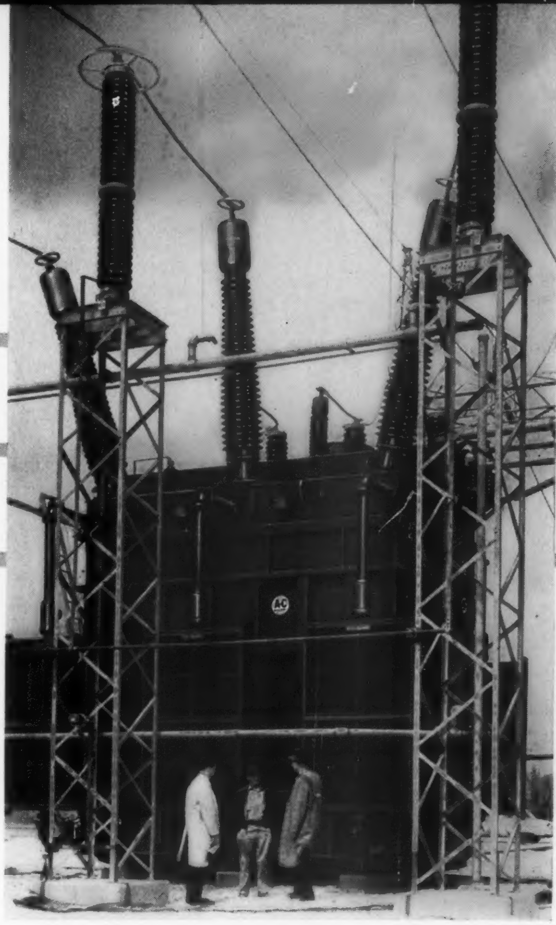
OIL
Advantages

1. Does not give off gas blast.
2. Does not require space for gas diffusion.
3. Replacement of parts less expensive.
4. Easy to service once tank is dropped.
5. Not affected by dust or corrosion.
6. Long mechanical life.
7. Can be used in hazardous areas.

AIR
Advantages

1. Longer contact life.
2. Cleaner maintenance.
3. No oil to test and maintain.
4. No oil to change.
5. Negligible fire hazard.
6. Designed for reversing jogging service.
7. Good for highly repetitive service.

ARE REDUCED INSULATION TRANSFORMERS SAFE?



AUTOTRANSFORMER built in 1957 for 345-kv service has 1050-BIL rating, or a reduction of two classes in insulation strength.

by J. R. MANN
Manager
Transformer Department
Allis-Chalmers Mfg. Co.

Answers to the reduced BIL question are based on arrester protection and transformer design.

DESPITE THE FACT that reduced insulation transformers have been applied on utility systems for over twenty years, the trend has not been completely adopted. Some apply units that are only one step reduced when a reduction of one and one-half steps is common and even two steps down are not unusual.

Reduced insulation transformers in voltages above 69 kv can show cost savings of millions of dollars annually, but engineers have been reluctant to take advantage of these savings because they aren't sure that the reduced insulation transformers are safe for their systems.

The present full insulation transformer test levels have remained virtually unchanged for nearly a half century. When they were established, there were no lightning arresters, no impulse tests, no switching surge tests, and very little engineering knowledge either of system overvoltages or transformer insulation strengths. Today, however, a great deal is known about each of these subjects, and a scientific approach to insulation coordination is possible.

Insulation coordination simply means knowing what service voltages are possible and supplying equipment that by demonstrated test will withstand these voltages.

Five voltages must be considered

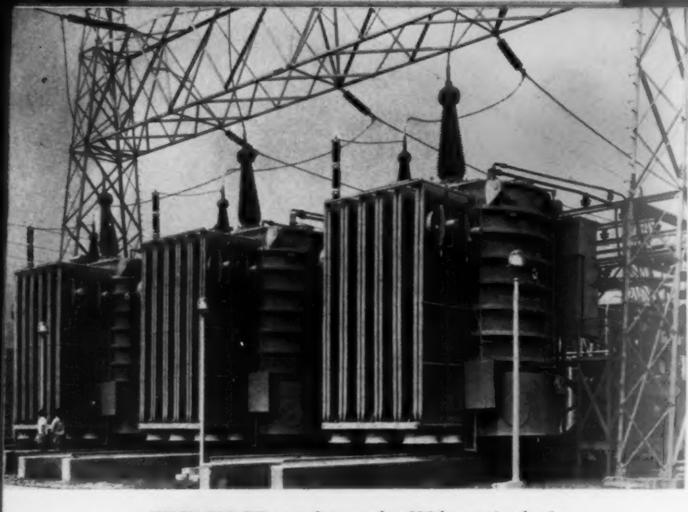
Many large industrial cities are now receiving their power at 230 kv. When thinking of operating voltages on such a system, we must consider five major types of operating voltages.

Normal continuous 60-cycle voltage

Obviously, one of the requirements of each winding is that it be insulated for the normal operating voltage. The line end of the high voltage of 230-kv side is normally at 133 kv above ground, and there must be insulation between that point and ground for this voltage.

60-cycle overvoltages

The transformer, however, does not always operate at 230 kv, since most transmission lines operate above their nominal values. The range allowed by ASA standards is 10 percent above the highest tap voltage of the transformer. Therefore 230-kv transformers with taps 10 percent above normal must be insulated to withstand 278 kv from line to line continuously. This increase brings the voltage from line to ground up to 161 kv.



FIRST 825-BIL transformers for 230-kv service having a 1½-class reduction in insulation were built in 1952.

SIX-TRACE moving film cathode-ray oscillograph is used to record wave patterns from switching surge tests.

Fault voltages

When a line-to-ground fault occurs on a Y-connected circuit, it is possible for the unfaulted phase voltages to rise as high as 173 percent of the normal line-to-neutral voltage. The voltage seldom rises to this value, since most systems have $X0/X1$ ratios that limit it to 140 percent or less. This 60-cycle sinusoidal voltage occurs only during line faults and on modern systems is limited to 226 kv or less on a 230-kv system.

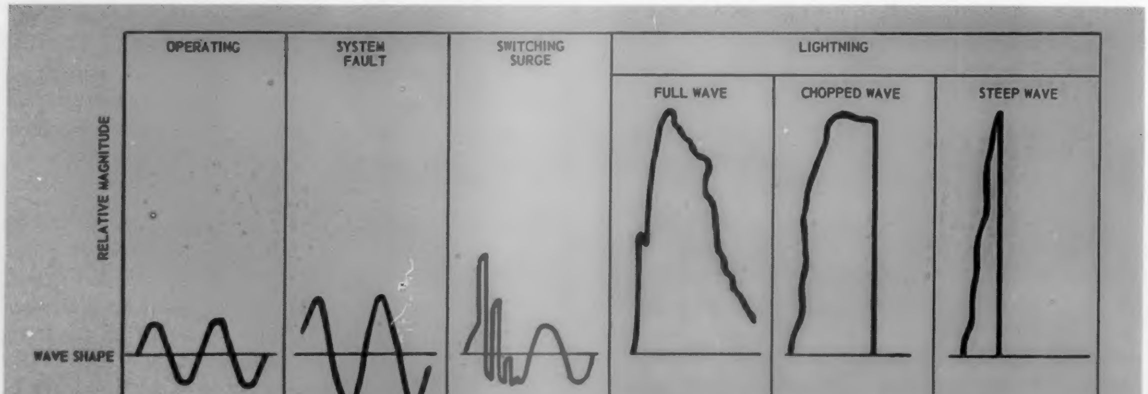
Switching surge voltages

When the transformer is switched or when the lines to which the transformer is connected are switched, voltage surges are produced which are different from either the normal operating voltage, the overvoltages associated with operation, or the overvoltages caused by faulted lines. These switching surges are a function of many factors, including line characteristics, length of lines involved, system interconnections, ability of the breakers to disconnect without restriking, and other complexities. The surge is an oscillation and might look something like that shown in Figure 2. Considerable work has been done and is being done to determine the magnitude of switching surges on practical operating lines. However, it appears that a switching surge crest on systems equipped with good breakers will not exceed a magnitude of two to three times the line-to-neutral voltage and a duration of three or four thousand microseconds.

It is reasonable to assume that windings of a 230-kv transformer should be designed for surges of 600-kv crest.

Lightning voltages

When lightning strikes the transmission lines, other voltages occur that must be taken into consideration. The lightning voltage, like the switching surge, has a shape and magnitude determined by several factors, including the flashover and impedance characteristics of the line, the distance of the stroke from the transformer, etc. In general, lightning voltages rise to maximum value in a very short length of time — a few microseconds or less. If flashover to ground occurs, voltage collapse will be rapid; if not, it may decay over a period of from 25 to several hundred microseconds. Typical wave shapes are shown in Figure 2. The magnitude of these voltages may reach crest values of six or more times the normal line-to-neutral operating voltage, depending upon the insulation



TRANSFORMER INSULATION may be exposed to these general types of voltage waves. **(FIGURE 1)**

DESIGNED IN 1933, 550-BIL transformers are still providing reliable service on 138-kv power system.

level of the transmission line. The transformer, therefore, must also be insulated for voltages in the order of 1,100,000 to 1,400,000 volts existing for 1 to 10 microseconds, unless these voltages are limited either by system design or lightning arresters.

The insulation design thus becomes complicated with requirements for voltages of different magnitudes and different wave shapes. Voltage wave shape is important because, together with the transformer's characteristics, it determines the distribution and magnitude of the voltage in the transformer. Configuration of the windings, capacitances and inductances in the winding, type and contours of the insulation structures, and characteristics of the insulating material — all control the voltage withstand strength of the winding.

Transformers and lightning arresters are coordinated

Today we know, with a reasonable degree of accuracy, the various system voltages possible and the withstand strength of the transformer.

The first coordination step is to choose a lightning arrester that will operate satisfactorily on the system and then pick a transformer insulation level that will fit the arrester characteristics.

Since the *IR* voltage across an arrester when discharging the standard 10 x 20 current wave is similar in shape to the full-wave voltage test of the transformer, the full wave of the transformer is generally the value that must be coordinated with the *IR* drop if the discharge current of the system is large. However, if the discharge current is small, the impulse sparkover values of the arrester may be higher than the *IR* drop, in which case the front-of-wave transformer strength may be compared with the front-of-wave arrester sparkover. Since the discharge currents of most high voltage systems are well below 20,000 amperes, generally arrester impulse sparkover may be used for arrester coordination.

It should also be noted that the actual full-wave strength of a transformer is practically the same as its chopped-wave strength, even though the test values would indicate it to be lower. Therefore the full-wave *IR* drop or 1½ x 40 sparkover of the arrester should actually be compared to the chopped-wave test to obtain a realistic comparison.

Table I shows the values for a 195-kv arrester that was available prior to 1950. Comparing these values to the withstand levels of a fully insulated 1050 BIL transformer shows one reason why engineers did not go all-out for reduced insulated units a decade ago. Note that although impulse sparkover values are well below the transformer withstand level, the switching surge sparkover is nearly identical to the transformer strength. This small margin may account for some of the failures which provided reasons for avoiding such applications.

The modern 195-kv arrester has a switching surge sparkover value nearly one third lower and will protect a 750 BIL transformer better than the old arrester protected a 1050 BIL unit, as shown in Table II. However, the usual practice is to use a 182-kv arrester to give an extra margin between insulation strength and protective levels.

AUTOTRANSFORMER for 161-kv service has 550-BIL rating. Without this two-class insulation reduction, the unit would have been substantially larger and 15 percent higher in price.

TABLE I						
Type of Voltage	Fault	Switching Surge	Lightning Surge			IR Drop 20,000 Amp
			FW	CW	SW	
1050 BIL Transformer Can Withstand	652	847	1050	1210	1400	1210
Arrester 195 Kv *	276	850 **	748	748	826	865

* Arrester available prior to 1950. All voltages are maximum crest values.
** Estimated value.

TABLE II						
Type of Voltage	Fault	Switching Surge	Lightning Surge			IR Drop 20,000 Amp
			FW	CW	SW	
750 BIL Transformer Can Withstand	460	600	750	865	1070	865
Arrester 182 Kv * 195 Kv *	 257 276	 548 583	 486 517	 486 517	 588 623	 573 613

* 1958 arresters. All values are maximum crest voltages.

On the basis of guaranteed arrester values and tested transformer strength, reduced insulation must be chosen.

60-cycle corona level is key to insulation life

Lower BIL units have a smaller margin between operating and withstand voltages. Instead of a low frequency test voltage twice the normal system voltage, the test for 750 BIL is only 1.4 times system voltage. Sixty-cycle corona becomes an increasingly important factor. It is possible for a transformer to "pass" normal factory tests and yet fail in service at operating voltages because of corona.

A test for corona is therefore necessary. Such a test has been developed and is being used today to demonstrate that truly corona-free transformers are being manufactured. These tests are under discussion in AIEE committees as well as by the International Electrotechnical Commission and new standards will undoubtedly result.

Coupled with the foregoing considerations is the confidence that further progress in lowering switching surge protective levels of lightning arresters or raising the switching surge strength of transformers will soon result in even greater reduction in transformer insulation levels.

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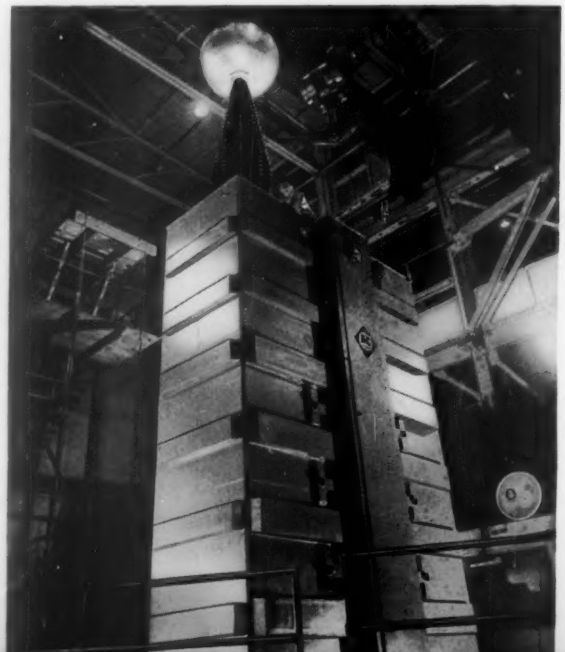
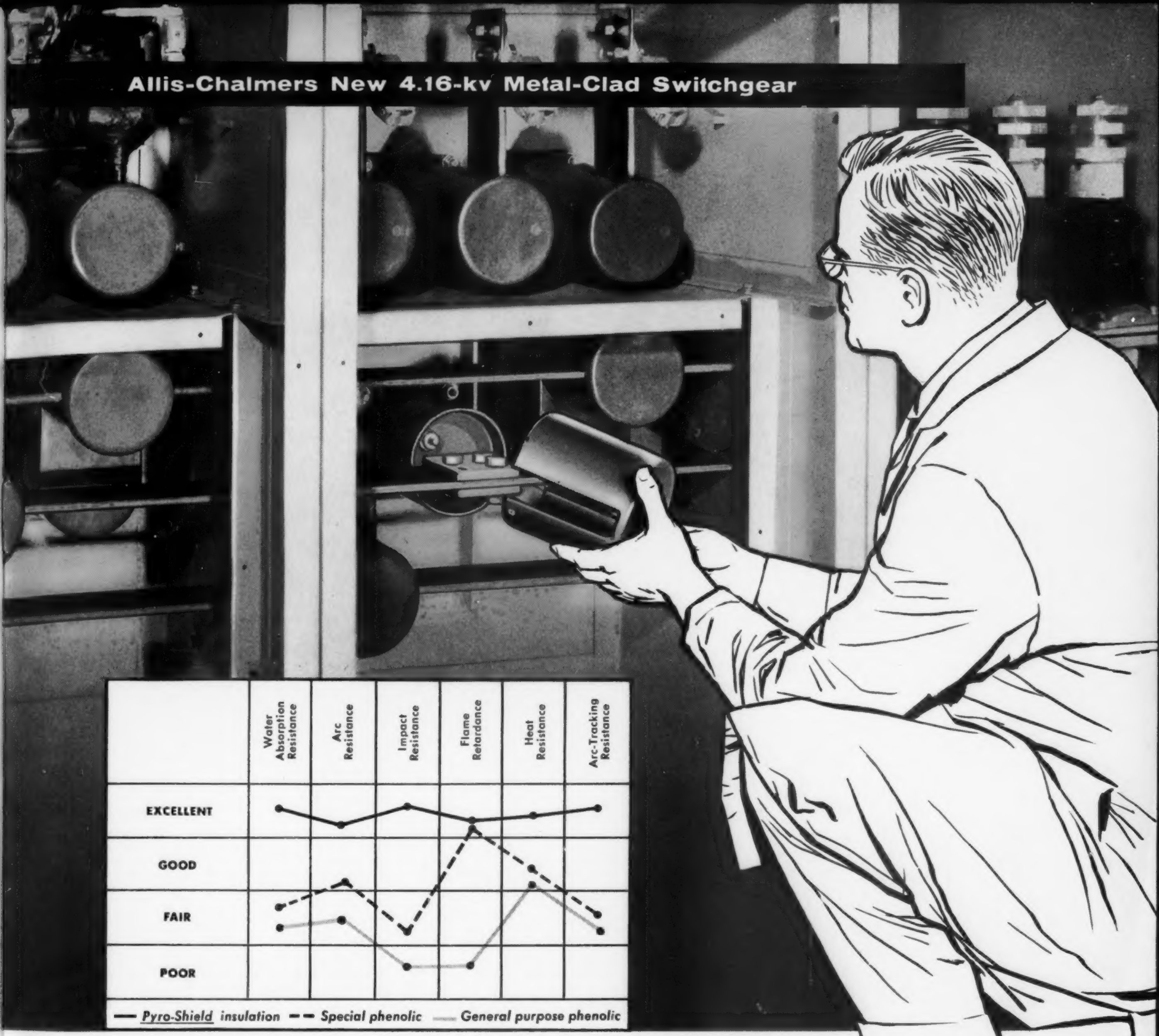


THEORETICAL MAXIMUM insulation class reduction was used in 1650-BIL experimental transformer for 600-kv service.



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Track-resistant *Pyro-Shield* insulation is a polyester glass base material now used in Allis-Chalmers co-ordinated system of switchgear insulation.

One molding connects primary disconnects to bus bars to provide uniform insulation and reduce the number of insulation components.

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Get details on this new insulation and other Allis-Chalmers switchgear features, including the low 72-inch silhouette and new *Shelter-Clad* design. Contact your nearby Allis-Chalmers office, or write Allis-Chalmers, Power Equipment Division, Milwaukee 1, Wisconsin.

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